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Risk Analysis of Conventional and Solo Watch Keeping

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Summary

As a part of the safety evaluation of trials with officers of the watch to act as the sole lookout during periods of darkness the Danish Maritime Administration has initiated the present study.

The objective is to compare a conventional bridge with solo watch keeping during the day and with a rating as lookout during the night with a bridge equipped for and having solo watch keeping during periods of darkness with the possibility to call a backup if necessary. The conventional bridge is a modern bridge and the main technical difference between the conventional bridge and the bridge allowing for solo watch keeping during periods of darkness is technical equipment in the form of a graphic position display system, an alarm transfer system, and improved bridge layout. The study compares these two systems and evaluates whether a vessel operated with solo watch keeping on an integrated bridge performs as well as a vessel with a conventional bridge having a rating lookout at night. The analysis takes into account that if conditions of weather, visibility, proximity of dangers to navigation, or traffic situation causes solo watch keeping being unsafe, then the Officer of the Watch on the bridge equipped for solo watch keeping will call a backup officer to the bridge. The analysis also takes into account that if similar conditions on a conventional bridge cause solo watch keeping during daylight to be unsafe, then the Officer of the Watch will call a rating lookout to the bridge.

The analysed critical situation, within which the two bridge systems are compared, is defined as:

> "*During the watch the considered vessel is on collision course with an object. Machinery and steering gear are functioning.*"

At the initial point of the analysis it is assumed that the collision object is so far away that the Officer of the Watch (OOW) has no means of detecting the object. The objective of the study is then to model *whether or not* the OOW is able to act in time such that the potential collision is avoided. It is hereby implicitly assumed that if the OOW acts in time, then the potential collision with the object is avoided. It is noted that the OOW not acting in time does not necessarily imply that a collision will take place. In this study we are not interested in identifying whether a collision actually occurs, but only in the probability of the OOW acting in time.

The analysis procedure is based on numerical evaluations using Bayesian Networks. Using Bayesian Networks allows for taking into account the time aspect in the analysis. To the authors' knowledge no other study has included the different time windows caused by changing visibility.

The results from the Bayesian Network have been sought verified by extending the model to estimate the probability that two large vessels on a collision course actually will collide. This comparison shows that the applied modelling results in probability levels of the correct order of magnitude. The established model has also been used to calculate the dependence of risk of collision on visibility. In accident statistics, registered from 1966 to 1971, the relationship between visual range and degree of risk has been evaluated by Japanese researchers [7] and the risk found to be approximately proportional to $1/r^{1.6}$, where r is the visibility. The present model gives proportionality factors that are lower ($1/r^{1.1}$), but comparable. A lower proportionality factor should be expected since radar technology has improved during the past three decades, and since the effect of the radar on the safety in low visibility is significant.

A comparison of probabilities that the OOW does not act in time on the conventional bridge with similar results for the OOW not acting in time on the solo watch bridge is shown in the following table.

P[OOW not acting] :	All weather conditions – all objects	
Case	**Conventional bridge**	**Solo Watch bridge**
Day and night	0.00270	0.00155
Daylight	0.00330	0.00141
Darkness	0.00209	0.00169

From this table it is seen that the probability that the OOW does not act is lower for the bridge equipped for solo watch keeping than for the conventional bridge. It is noted that the above probabilities account for terminated solo watches due to reduced visibility both on the conventional bridge during daylight and on the solo watch keeping bridge day and night.

Danish ships with bridges equipped for solo watch keeping at night have in addition to the alarm safety system, which ensures that an alert officer is present at the bridge, also an off-track and collision warning system connected to the alarm safety system. The effect of this system to call a backup if the OOW fails to act is not included in the present analysis. However, it is evident that the effect will further reduce the probability that the OOW on the bridge equipped for solo watch keeping does not act.

Therefore, the conclusion of the present study is that solo watch keeping during day and night on an integrated bridge is safer than a conventional bridge with solo watch keeping during day and watch keeping together with a rating as look out during night.

Introduction

The purpose of this report is to present a quantitative study of the risk associated with solo watch keeping at night in good weather conditions and low ship traffic at open sea. This is done by quantifying the difference in risk between on one hand a ship with an integrated bridge system operated with one man on the bridge also at night and on the other hand a similar ship with a conventional bridge system where besides the navigator also a rating is assigned as lookout during periods of darkness. The analysis procedure is based on numerical evaluations performed by means of a Bayesian Network.

Several studies with the same objective have been performed recently. Det Norske Veritas [1] have presented an assessment of the navigational risk associated with the bridge design described in MSC/Circ. 566 with one officer on watch and dispensing with the dedicated lookout in normal visibility. This risk is compared to the risk associated with the conventional bridge with one officer on watch and lookout at night as a routine. The analysis is based on fault tree assessment of failure when a ship is on a dangerous course. The conclusion of the DNV study is that the sole lookout on an integrated bridge reduces the mean navigational risk.

In a comprehensive report initiated by order of the German Federal Ministry of Transport Froese et. al. [2] described the background for the international development towards a set of IMO requirements for tests with solo watch keeping during periods of darkness. In this report is presented a comparative risk assessment using the first two steps in a formal safety assessment, i.e. identification of the hazards and the assessment of risks associated with those hazards using event tree analyses. The result show that the better technical equipment compared to the conventional ships combined with an effective organisation with quick availability of a qualified backup compensates for the absence of an additional rating.

In The Netherlands Schraagen et. al. from TNO Human Factors Research Institute [3] carried out a study to determine whether a single person on an integrated bridge provides at least the same degree of safety as in cases where two persons on a conventional bridge fulfil the function. The study includes on-board observations as well as controlled simulator studies. The onboard observations were carried out both on conventional and on integrated bridges where the integrated bridges conform to the “Draft requirements for solo watch keeping during periods of darkness” (NAV 40/25, Annex 18). The observations show that due to the improved navigational aids on the integrated bridge the Officer of the Watch (OOW) acting as the sole lookout spent more time on lookout than the OOW on conventional bridges. The simulator study was carried out in conditions, which are unlikely for sole lookout situations. But even under these conditions the report concludes that the presence of a lookout does not result in a higher percentage of visual detection of objects on the sea, and that the presence of rating as lookout does not lead to lower workload of the OOW. Altogether the Dutch study found that on integrated bridges with the OOW acting as sole lookout, at least the same degree of safety can be provided as on conventional bridges.

For the Swedish Maritime Administration Wikman and Andersson [4] have performed fault tree analyses for various bridge designs manned with one officer alone. The safety of these designs has been compared to the safety of a conventional bridge with one officer and one lookout. That is, the conventional bridge is such that if it is provided with a system which verifies the alertness of the navigational watch officer at intervals not exceeding twelve minutes it will fulfil the requirements for a sole lookout bridge according to MSC/Circ. 566. The results of this study show that collision warning and grounding systems connected to an alarm transfer system significantly increases the safety of the ships with sole lookout compared to a conventional bridge. The analysis also shows that the simple alertness alarm transfer system is not sufficient to replace a rating as lookout.

Besides these in-depth analyses statistical results of trials with one-man bridge operation during periods of darkness have been carried out during the trial period, see Ref. [5].

Finally, it can be mentioned that tests are presently conducted with one-man bridge operation even along heavily trafficked coastal routes, see for instance [6]. These vessels have been equipped with an integrated navigation system that includes special features such as audio input and output equipment as the main man-machine interface between the navigator and the integrated navigation system. Besides such features, the integrated navigation system also includes a stranding and collision avoidance system, which automatically plans a route for the ship to take in order to avoid such potential dangers.

In the present investigation we shall supplement the above mentioned previous studies by carrying out a risk analysis which takes into account the time aspect.

Objective of the study

The objective of the present study is all in all to compare a vessel with a modern conventional bridge and a rating as lookout at night with a vessel with a bridge equipped for and having solo watch keeping during periods of darkness. As described in Ref. [3] the technical difference between the two bridge types is that the bridge allowing for solo watch keeping is equipped with a graphic position display, an alarm transfer system, and an improved bridge layout. The task of the study is therefore – by some means – to compare these two systems and to evaluate whether a vessel operated with solo watch keeping during periods of darkness performs as well as a vessel operated with a rating at night on a modern conventional bridge. The analysis must take into account that if conditions of weather, visibility, or traffic situation causes solo watch keeping being unsafe, then the Officer of the Watch will call a backup officer to the bridge. The analysis must also take into account that if similar conditions on a conventional bridge cause solo watch keeping during daylight to be unsafe, then the Officer of the Watch will call a rating lookout to the bridge.

To compare the two bridges we will in this study model a given critical situation and compare the performance of the two bridges within this model universe. The considered critical situation and the interpretation of the critical situation are qualitatively described in the next section.

Qualitative description of the considered critical situation

It is generally accepted that most collisions between ships can be attributed to human failure. Anyway, in the present analysis it is assumed that the machinery and the steering gear are functioning. Therefore, an analysis of collision rates must be based on a study of the navigator's role in resolving critical situations. In the present investigation we have chosen to break the work of the Officer of the Watch (OOW) down into four cognitive phases:

1. Perception of the situation. Visual realisation of the presence of other ships or floating objects or perception of other ships or floating objects by instruments such as radar, radio etc.

2. Assessment of the perceived information either mentally or using auxiliary devices for plotting, computing etc. From the moment the OOW realises that a ship or an object is present in the vicinity of his own vessel it will take him some time to determine the relative speed vector such that he can decide whether there is a situation on which he has to react.

3. Decision-making based on the assessment of the current situation taking into account the traffic situation, manoeuvring capabilities etc.

4. Action in the form of new navigational courses or changes in speed.

In the following study of the effect of solo watch keeping we shall restrict the analysis to the phases 1 and 2. In the analysis we consider a specific critical situation occurring during a watch keeping. The considered situation is defined as:

> "*During the watch the considered vessel is on collision course with an object. Moreover, machinery and steering gear are functioning.*"

The definition of "a collision" should be considered in a broader perspective than just a physical collision. Considering safe navigational operation, collision in this context also includes passages within a (vaguely defined) safe domain of the vessel and the object.

At the initial point of the analysis it is assumed that the collision object is so far away that the OOW has no means of detecting the object. The objective of the study is then to model *whether or not* the OOW is able to act in time such that the potential collision is avoided. It is hereby implicitly assumed that if the OOW acts in time, then the potential collision with the object is avoided. It is noted that the OOW not acting in time does not necessarily imply that a collision will take place. If the potential collision object itself is able to evade, then a collision may not take place. This would be the case if the potential collision object were a vessel since this, of course, might be able to counteract the risk of collision, whereas a floating object would not. In this study we are, however, not interested in identifying whether a collision actually occur, but only in the probability of the OOW acting in time.

The considered critical situation and the primary model parameters are illustrated below:

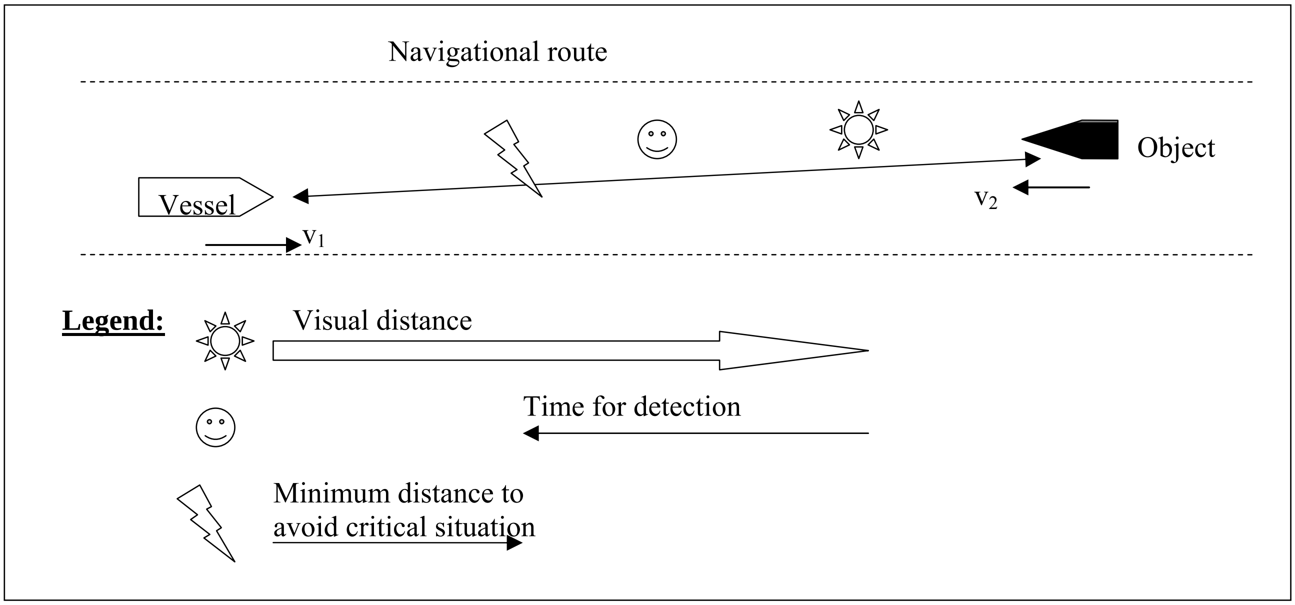


Figure 1: *Illustration of the considered critical situation.*

The figure shows the considered vessel with speed v_1 and the object with speed v_2 with which the vessel is on collision course. The legend in the figure explains the case of a visual detection. The object may in general be detected either visually or by means of the radar. The basic mechanisms in visual and radar detection are, however, similar, and a same type of legend to the one given in the figure may therefore be established for radar detection.

In the explanation of the primary modelling parameters we consider, as shown in Figure 1, the case of a visual detection. The figure shows that, at the initial point of the analysis, the object is so far away that the OOW has no means of detecting the object. When the object is within a certain range from the vessel (illustrated by the sun in the figure) the object may be detected. This situation represents the above-mentioned phase 1 of the cognitive process. The visual distance will be dependent on visibility and on the type of object.

In order to assess the perceived information (phase 2) and to perform an evasive manoeuvre to avoid collision with the object the vessel will need at least a specified minimum distance. This minimum distance is shown as the lightning in the figure. The minimum distance required to perform the evasive manoeuvre is dependent on the size and manoeuvrability of the considered vessel, the vessel speed, and on the conditions of the navigational route. The conditions of the navigational route will be dependent on the traffic density and on the confinement of the navigational route.

The distance between the visual distance and the required minimum distance for performing an evasive manoeuvre defines the distance within which the OOW must detect the object in order to be able to act in time. This distance may be converted into a time period within which the OOW (or lookout) must detect the object. The available time period is defined in terms of the relative speed between the vessel and the object.

When the lookout duty takes place a certain time period will elapse before the lookout has scanned the sea surface for potential objects, say 360-degree. Even if the lookout duty is performed at a highly skilled and concentrated level there will always be a probability of the lookout not seeing an object when this is within the detectable zone. Sometimes even the concentrated lookout will require two or more scanning of the sea surface before the object is identified. Moreover, all personnel on the bridge will be engaged in different tasks. These tasks will interact with the person's ability of performing the lookout duty and divide the persons attention between the different task. Finally, if too much external interference occur, then the person on the bridge may feel stressful and consequently divide his attention to the different required tasks in an irrational manner causing further increase in the time for scanning the sea surface.

A detection model for radar detection may be formulated in a way similar to the above given visual detection model. If either a visual detection or radar detection has taken place then it is assumed the OOW has assessed the situation and will act and thereby avoid the collision.

The comparative risk analysis of conventional and solo watch keeping should be able to capture the above model. It may be argued that conventional and solo watch keeping will only differ in the number of personnel on the bridge and instrumentation, and any study should therefore concentrate only on the manner the OOW and other personnel divides their attention between the different tasks to be performed. We certainly agree on the vital importance of the performance of the personnel on the bridge, but find it paramount that the risk analysis evaluates the consequences of the performance in a proper perspective. Unfortunately, conventional risk analyses may be defeated by application to the present problem formulation, and the risk analysis therefore calls for alternative tools. One such tool is described in the subsequent section.

Motivation for introducing Bayesian networks

Most practical risk analysis problems are characterised by a large set of interrelated uncertain quantities and alternatives. Within the conventional risk analysis different methods such as fault tree analysis and event tree analysis have been developed to address these problems. A fault tree analysis seeks the causes of a given event, and an event tree analysis seeks the consequences of a given event. The two analysis techniques are supplementary methods, and when applied correctly the formulated model may reveal the entire probability structure of the model. Both fault tree analysis and event tree analysis – applied separately and combined – have in the past with success been used in the evaluation of the risk of various hazardous activities. Unfortunately, both fault tree and event tree analyses do have their drawbacks. Firstly, it is difficult to include conditional dependencies and mutually exclusive events in a fault tree analysis (a conditional dependency is, for example, the dependence of the visibility on the weather; mutually exclusive events are, for example, good weather and storm). If conditional dependencies and mutually exclusive events are included in a fault tree analysis the implementation and the pursuing analysis must be performed with utmost care. Secondly, the size of an event tree increases exponentially in the number of variables. Thirdly, the global model, which is combined fault trees and event trees, generally becomes so big that it is virtually impossible for third parties (and sometimes even for first parties) to validate the model.

A Bayesian Network is a graphical representation of uncertain quantities (and decisions) that explicitly reveals the probabilistic dependence between the set of variables and the flow of information in the model. A Bayesian Network is designed as a knowledge representation of the considered problem and may therefore be considered as the proper vehicle to bridge the gap between analysis and formulation.

A Bayesian Network is a network with directed arcs and no cycles. The nodes (to which the arcs point) represent random variables and decisions. Arcs into random variables indicate probabilistic dependence, while arcs into decisions specify the information available at the time of the decision. As an example, one node in the network may represent the weather, whereas another may represent the visibility. An arc from weather to visibility indicates that visibility is conditionally dependent on weather. The diagram is compact and intuitive, emphasising the relationship among the variables, and yet it represents a complete probabilistic description of the problem. For example, it is easy to convert any event tree or fault tree into a Bayesian Network. Conversely, it may not always be an easy task to convert a Bayesian Network into a combined fault tree and event tree.

A drawback of Bayesian Network is that they require the state space of the random variables (the nodes) to be defined as discrete states. In our above-mentioned example of weather and visibility, the state space of weather may easily be discretised into states as good weather, storm, etc., whereas the state for visibility more naturally would have been defined as a continuous state space. The Bayesian Network modelling does, unfortunately, require the state space of visibility to be discretised in ranges as for example, 0 to 1 km, 1 to 2 km, etc. Although this is mentioned as a drawback, neither fault trees nor event trees offer any better alternatives. A consequence of the discretisation is partly that the result of the Bayesian Network may be sensitive to the selected discretisation, and partly that the calculations involved in the evaluation of the Bayesian Network grow almost exponentially in the number of states of the nodes. The latter is a consequence of Bayesian Networks encodes the entire probabilistic structure of the problem.

A focus on the causal relationship among the variables most effectively does the building of a Bayesian Network. This implies that a Bayesian Network becomes a reasonable realistic model of the problem domain that is useful when we try to get an understanding about a problem domain. In addition, knowledge of causal relationships allows us to make predictions in the presence of interventions. Last, but not least, the model building through causal relationship makes it much easier to validate and convey the model to third parties.

We will not give any details here on how Bayesian networks are analysed. Instead reference is left to Jensen [10] and Pearl [11].

Qualitative description of the formulated Bayesian network.

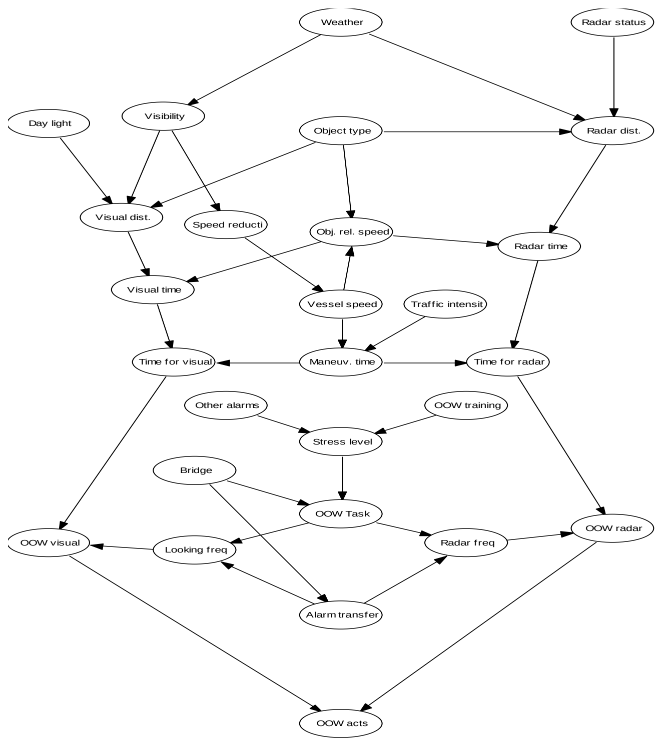
This section gives a qualitative description of the Bayesian network established for analysis of the risk associated with sole lookout. The objective is to convey the idea of building the network through the causal relationship among the variables. In the building process we will describe modelling aspects of the nodes and for some also describe their actual states. The subsequent section will give a thorough description of the states of each node and how the conditional probability distribution is assigned.

The network presented in this section, aims only at describing the tasks of the Officer of the Watch (OOW). The network does thereby neither represent a model of a conventional bridge nor a bridge allowing solo watch keeping but a system which is relevant for both of these two bridge types. When this part of the Bayesian network is properly modelled and understood, it is straightforward to add effects of rating lookout or calling a backup in a critical situation.

Figure 2: *Bayesian Network for Officer of the Watch. The network defines the common part for both the conventional bridge and the solo watch keeping bridge.*

As already described the network aims at modelling a specific situation where the considered vessel is on collision course with a given object. The objective of the network is then to model whether or not the OOW acts in time such that the potential collision is avoided.

The OOW has two different means of detecting the particular object: either visually or by means of the radar equipment. The left and right hand sides of the network given in Figure 2 relate to these detection means, respectively. The top node of the network is the "Weather". The weather is modelled as having the states "Good weather", "Storm", "Rain or Snow", "Heavy rain" and "Fog". The condition of the weather clearly has influence on the visibility. The node "Visibility" defines the meteorological visibility and is modelled as a distance in kilometres. The node "Visual dist." describes the maximum distance a given object may be visually detected. It should be understood that the visual distance is the distance at which a lookout first may identify and interpret an object knowing that a specific object eventually will appear in a given direction. The visual distance is dependent on the considered type of object, whether the object is sought detected during day or at night, and on the meteorological visibility. The node "Daylight" models



the condition of the day, and the node "Object" models the considered potential collision objects. As potential collision objects we in this study consider "Large vessels", "Small vessels", and "Floating objects". Returning to the node "Visual dist.", it is noted that during night the possibility of detecting both a large and a small vessel are almost identical since it is the lights of the vessels that are identified whereas the difference is larger for the situation during day. The formulated causal relationship allows for taking these effects into account.

Not only the visibility but also the detection range of the radar is dependent on both the weather, the object, and, of course, on whether the radar is functioning or not. The node "Radar status" gives the status of the radar. In case of a storm, sea clutter may affect the detection range of the radar whereas heavy rain may cause rain clutter and thereby cause shielding of objects behind the rain cloud. It is assumed that (light) rain or snow has no impact on the detection range of the radar, but only on the visibility. The node "Radar dist." models the maximum detection range of the radar. Distances up to 16 nautical miles are considered as the relevant range of the radar. It is noted that the node “Object” has a causal link to both the node “Visual dist.” and the node “Radar dist.”. This implies that the network becomes able to model correlation between the visual distance and the radar range. Consider, for example, a floating object, which hardly is detectable on the radar but also, difficult to visually detect, especially in darkness. The modelling of the network assures that such dependencies are captured.

Given the maximum distance for visual detection and for radar detection, the next task is to transform this distance into a time period within which either visual detection or detection by means of the radar must take place. This time period is directly related to the relative speed between the object and the modelled vessel. The relative speed is given in knots and is described by the node “Obj. rel. speed”. As seen in Figure 2 the relative speed is dependent on not only the node “Vessel speed” but also the node “Object type” since the three considered objects must be expected to travel with different speeds and courses. Knowing the relative speed and the visual or radar distance to the object, it is a simple task to calculate the time within which the object may be identified either visually or by the radar. The two nodes “Visual time” and “Radar time” give the required time in minutes. It is noted that the vessel speed is dependent on whether a “Speed Reduction” has taken place. The node “Speed reduction” defines whether reduced visibility causes a speed reduction to take place.

However, to avoid the potential collision with the object it is not sufficient just to identify the object within the visible time or the radar time, since also the required time (or distance if preferred) for performing the required evasive manoeuvre must be accounted for. The node “Maneuv. time” describes the required manoeuvring time and is dependent on both vessel speed and traffic intensity. The causal dependency of the manoeuvring time on the traffic intensity implies that an evasive manoeuvre will require longer time in a relatively high trafficked (or confined) area than in a low trafficked area. The node “Traffic intensity” is modelled with the states “Low”, “Medium”, and “High”. Knowing the required manoeuvring time, the “Time for visual” and “Time for radar” are simply established by subtracting the manoeuvring time from the visual or the radar time.

The part of the network that we have described until now models the physical boundaries of the considered collision problem. The next step is to identify whether the OOW manages to detect the object either visually or by means of the radar within the available time period. The physical boundaries of the network are more or less apparent, whereas modelling of the OOW reaction system is more disputable since it involves the modelling of the human aspects. We have selected the following causal modelling.

The stress level of the OOW is causal dependent on both the training levels of the OOW and on the number of other alarms or unforeseen action the OOW must confront during watch keeping. The node “Other alarms” defines the expected number of alarms and the node “OOW training” is modelled as “Low”, “Medium”, or “High”. The node “Stress level” defines the stress level in terms of “Low”, “Medium”, or “High”. The stress level influences the ability of the OOW to rationally divide his attention between the different tasks he must handle. The node “OOW task” contains the states “World”, “Radar”, and “Other”. “World” meaning that the primary task of the OOW at the instant in time is to perform the lookout duty, “Radar” meaning that the primary task is to interpret the radar signal, whereas “Other” covers other duties such as correcting charts, time tables, toilet, etc. It is noted that the node “Bridge” also has an influence on the task of the OOW. This dependency is included in the network for clarity, since the time available for performing the different tasks differs for the two bridge systems. This is because the solo watch keeping bridge is equipped with a graphic position display and therefore allows for a different fraction of time spent on the considered tasks.

Both the frequency with which the OOW scans the sea surface (node "Looking freq.") and the frequency with which the OOW scans the radar (node "Radar freq.") is influenced by the current task of the OOW. These frequencies are also dependent on the node "Alarm transfer" which again is dependent on actual bridge type. A solo watch keeping bridge is equipped with an alarm transfer system that requires the OOW to react to this system within given time intervals. Typically the time interval will be set to 10 minutes. The impact of the alarm transfer system in the modelling is that the looking frequency and the radar frequency cannot exceed this limit (this, however, does not imply that the detection time will be less than 10 minutes). Considering the looking frequency, this frequency models a shorter duration of a scanning of the sea surface in the case of the OOW performing the lookout duty. The OOW being looking at the radar does not imply that he will not be scanning the sea surface. His mind will be concentrated on the radar, but he will even though look up with intervals to scan the sea surface. The impact is that the duration of the scanning of the sea surface will be longer. Similar for the case when the OOW is performing other duties. The radar frequency is modelled similarly.

Whether the OOW is able to detect the object depends on the time for visual observation and the looking frequency. As previously mentioned the looking frequency models the time duration of one scanning of the sea surface. One such scanning does, however, not imply that the OOW surely will detect the object. Sometimes several scans of the sea surface would be required before the object is detected. The node "OOW visual" models the possibility of the OOW being able to detect the object within the available time period. The node "OOW radar" is modelled in a similar manner.

Finally, the OOW acting is dependent on either visual or radar detection. The node "OOW acts" describes this.

In a following section the network described above will be extended to specifically model the conventional bridge and the solo watch keeping bridge. The upper half of the network remains unchanged for cases when either a rating or a backup is present at the bridge. For the case when a Backup is present, the lower part of the network (below "Time for visual" and "Time for radar") will be duplicated. For the case of a rating being present, the lower left side of the network will be duplicated.

Assigned conditional probability distributions

In this section we describe the assigned conditional probability distributions to all the nodes introduced in the previous section. The assigned probabilities are for some nodes based on available statistics or defined through mathematical relations. For other nodes the conditional probabilities are estimated based on subjective expert judgement. The basis for the assigned probability distributions will be clearly stated. The table below gives an overview of the basis for the assessment of the conditional probability distributions.

Node	**Statistics**	**Mathematical**	**Subjective**
Weather	√		
Visibility	√		(√)
Object type			√

Daylight	√		
Visual distance			√
Radar status	√		
Radar distance			√
Vessel speed		√	
Object relative speed		√	(√)
Visual time		√	
Radar time		√	
Traffic intensity			√
Manoeuvring time			√
Time for visual		√	
Time for radar		√	
Other alarms	(√)		√
OOW training	√		
Stress level			√
OOW task			√
Alarm transfer	√		(√)
Looking frequency			√
Radar frequency			√
OOW visual		√	
OOW radar		√	
OOW acts		√	

Weather

The statistical data for weather is obtained from Sparre [8] who reports statistics of wind, visibility, air temperature, cloud amount, and weather recorded for 13 different light vessels located in Danish waters in the period from 1931 to 1960. Most of the light vessels have been located in inner Danish Water. Appendix A summarises the statistic for data recorded at the light vessel Vy1. This vessel is located in the North Sea and the available data is therefore judged to be applicable for the present study. More precisely, Vy1 was located approximately at 55°23'N and 7°36'E. Vy1 was not operating during the Second World War. Each day six observations have been made. The observation were performed at 4 a.m., 8 a.m., 12 noon, 4 p.m., 8 p.m., and 12 midnight C.E.T. (Danish time). Although [8] only reports limited information on the correlation between the recordings of weather and visibility, the data have been found relevant for the present study.

In the modelling the following states are defined relevant for representing the weather - or rather for modelling the influence of weather on visibility and radar performance:

Weather type	Number of days
Good	327
Storm	14
Rain or snow	19
Heavy rain	0.5
Fog	4.5

The considered weather types and the associated number of days of occurrences are identified on the following basis:

Fog: It is assumed that fog causes visibility to be less than 1 km and that fog only may occur when the Beaufort number is between two and four. Assuming further that 75% of all visibility less than 1 km are due to fog, the probability of fog may be found by a summation over Beaufort wind speeds 2, 3, and 4, and subsequently multiplying this value by 0.75.

Rain and snow: The annual average number of days with rain from 1931 to 1960 is given in [9] as 16 days. The number of days with rain cannot be deduced from the Light vessel data [9] described in the previous section since that study registered occurrence of precipitation in any degree during the day. However, 16 days of rain appears to be reasonable by comparing to the 12.2 days of registered thunderstorms and 11.2 days of registered hail given in [8]. No data was found which defined the number of days with heavy snow. Ref. [8] indicates that snow in average is experienced 25 days of the year. It is assumed that heavy snow occurs 3 days of the year. In total, the modelling therefore assumes that rain or snow is experienced 19 days of the year.

Heavy rain: No data was found which defined the number of days with heavy rain. However, Ref. [8] report 12.2 days of registered thunderstorms and 11.2 days of registered hail. It is therefore assumed that heavy rain occur ½ a day of the year.

Good weather: Good weather is defined as weather with large visibility and wind speeds less than or equal to 6 Beaufort. The resulting number of days is extracted from [8] as the number of days with Beaufort Nos. less than or equal to 6 and subtracting days with rain, snow or fog. Good weather is present 327 days of the year.

Storm: Storm is defined as Beaufort wind speeds larger than or equal to 7. Storm is present 14.5 days of the year.

Visibility

The node "Visibility" defines the probability distribution for the visibility conditional on the weather. As no study has been identified which defines the required basis, these distributions have been established on a subjective basis. As background material for the subjective assessment Tables in the Appendix give the marginal distribution for the visibility and correlation between wind speeds and visibility. In the assignment of the conditional probability density functions it was required that the resulting assigned marginal cumulative density function should agree with the observed cumulative density function for the visibility. The assigned conditional probability density functions have been estimated in terms of truncated Weibull distributions. These continuous distributions are afterwards discretised. The upper truncation limit on the visibility is 60 km; that is, in the modelling it is assumed that visibility larger than 60 km cannot occur. The truncation limit has only impact on the distribution for the visibility in good weather. The assumed distributions for visibility are given below.

The format of the truncated Weibull distribution is

$$F(x) = [1 - \exp(\alpha(x-\gamma)^{\beta}]/C \quad ; \quad x \geq \gamma$$

In which α and β are distribution parameters, γ is the lower truncation level, and C is a normalising constant assuring that F(60 km) = 1.

The parameters describing the obtained Weibull distributions are:

Weather	**Good**	**Storm**	**Rain / snow**	**Heavy rain**	**Fog**
α	0.01174	1.007E-04	0.4083	1.910	1.910
β	0.674	4.714	0.746	0.749	0.749
γ	10.0	0.40	0.10	0.0	0.0

Figures in Appendix A show the estimated conditional density functions for visibility. These figures also compare the obtained marginal distribution for visibility with the observed distribution. For information only, the expected visibility conditional on the different weather conditions is given below. These values give an indication of the implication of the weather definition.

Weather	**Good**	**Storm**	**Rain/ snow**	**Heavy rain**	**Fog**
Expected visibility	28.9 km	6.8 km	4.0 km	0.45 km	0.45 km

In the Bayesian network modelling, the discrete domain of the node visibility contains 30 intervals, and the division in kilometres among these are: 0.25; 0.5; 0.75; 1; 1.25; 1.5; 1.75; 2; 2.5; 3; 3.5; 4; 4.5; 5; 5.5; 6; 6.5; 7; 7.5; 8; 8.5; 9; 9.5; 10; 12.5; 15; 17.5; 20; 25; 30. An argumentation for the selection of the upper limit is given under node "Visual distance".

Object type

Three different types of objects are considered relevant for the analysis. These are large vessels, small vessels, and floating objects. We have not specified any firm definition of the boundary between large and small vessels, but vessels with length less than 75 m belongs to our defined class of small vessel. The assigned probability distribution is

Type	**Probability**
Large vessels	600 / 1000
Small vessels	399 / 1000
Floating objects	1 / 1000

Floating objects are slowly moving objects and they are not visible on radar. The estimated number of floating objects is probably too high. The reason for this choice is to ensure a fair comparison where the probability for collision will be conservative for the solo watch bridge.

Daylight

The node "Daylight" contains the states "Daylight" and "Darkness". Both states are given 50% of probability.

Visual distance

The visual distance is defined as the maximum distance a qualified lookout may detect a given object. The visual distance is defined conditional on the visibility, the type of object, and whether the observation takes place during daylight or darkness. In clear weather the maximum visual distance between two ships depends on the distance the observer is lifted above the water surface and the air-draft of the ship on collision course. The air-draft of a ship is defined as height from the baseline to the top of the deckhouse less the (water) draft. Based on a series of measurements on drawings the average air-draft for large ships is taken as 25 m and for small ships the average air-draft is taken as 12 m.

If we assume that the observer is placed 23 m above the sea surface on a large vessel then the visual distances based on the visible horizon will be 38 km for observation of large vessels and 32 km for observation of small vessels. Similarly, if the observer is placed 9 m above the sea surface on a small vessel the calculated visual distance is 31 km for large vessels and 24 km for small vessels. These considerations leads to that the node “Visual distance” is subdivided into the same set of states as the visibility, that is 30 states.

Since the total table for the node contains in total $30 \cdot 30 \cdot 32 = 5400$ entries (with the majority of these being zero) we will not give the total table, but only describe the idea behind the assignment of the conditional probabilities.

1. The visual distance cannot exceed the visibility, which implies the probability of experiencing any visual distances beyond which the given visibility is zero.

2. A floating object is during daylight assumed to be detectable up to a maximum distance of 2 km, whereas during darkness this maximum is 0.5 km. These maximums are, of course, dependent on the visibility. Due to different types of floating objects it is assumed that visual distance of a floating object is triangularly distributed between 0.25 km and the maximum value with the most likely value equal to 0.25 km.

3. Large vessels are during daylight assumed to be visible at a distance equal to the visibility.

4. Small vessels are during daylight assumed visible at a distance equal to the visibility provided that the visibility is less than 9.5 km. For visibility larger than 9.5 km a triangular distribution is applied with the most likely value being 9.5 km and the upper limit equal to the visibility.

5. During darkness large vessels are assumed to be visible at a maximum distance from 15 km to 20 km (8–10 nautical miles). A triangular distribution is assigned with a most likely value equal to 15 km. For lower visibility ranges, the distribution is truncated accordingly.

6. During darkness small vessels are assumed to be visible at a maximum distance from 10 km to 20 km (6–10 nautical miles). A triangular distribution is assigned with a most likely value equal to 10 km. For lower visibility ranges, the distribution is truncated accordingly.

Radar status

The radar status has the states “Fault” and “OK”. On the basis of the DNV study [1] the probability of experiencing a radar fault during a watch is $5 \cdot 10^{-5}$. The assigned failure probability is estimated under the condition that the radar is checked prior to each watch shift.

Radar distance

The radar distance is defined as the maximum distance at which a given object may be identified with position and course on the radar. The radar distance is defined conditional on the weather, the type of object, and the status of the radar. Like in the modelling of the visual distance, the node "Radar distance" is subdivided into the same set of states, that is 30 states. This range reflects the standard setting of most radar within 12 to 16 nautical miles Also this node contains so many states that we also here will describe the modelling verbally.

1. If the radar is in a fault condition the radar distance is defined to be 0 km.

2. A floating object is assumed not to be detectable by the radar. The radar distance is therefore set to 0 km.

3. In good weather, in rain/snow, and in fog large and small vessels are assumed to be detectable in the range from 20 to 30 kilometres. A triangular distribution is assigned within this range with a most likely value of 30 km. This implies that in good weather a vessel is expected detected with position and course by the radar at approximately 13 nautical miles.

4. In heavy rain radar the detection distance for large and small vessels is given a uniform distribution from 0 to 30 km. A uniform distribution is assigned because rain clutter will affect the capabilities of the radar.

5. In storm wave clutter and effects of large waves may impinge on the radar detection ability. Modern radar technology, however, is able to correct for a large amount of these effects. In the modelling we have assumed that 95% of all large vessels are detected as well as in good weather. Because of wave clutter, the remaining 5% are given a uniform distribution between 0 km to 20 km. For small vessels 75% are assumed detected as well as in good weather. The remaining 25% are uniformly detected at distances between 0 to 20 km.

Speed reduction

In conditions with low visibility some ships will reduce their speed. However, in open sea the reduction is judged to be low.

For visibility less than 250 m one out of twenty ships are assumed to reduce speed to half the normal speed and with a visibility larger than one kilometre no ships will reduce their speed. The modelled fraction of vessels reducing speed is given below:

Distance	0.25 km	0.5 km	0.75 km	1.0 km
Probability of speed reduction	1 / 20	1 / 50	1 / 100	1 / 1000

Vessel speed

Only a single vessel speed is considered namely 15 knots. When speed reduction takes place, speed is assumed reduced to 7.5 knots.

Object relative speed

The object relative speed models the relative speed and course between the vessel and the object. The node is defined conditional on both vessel speed and object type. The maximum projected speeds of the considered objects are:

Object	Maximum speed
Large vessels	15 knots
Small vessels	10 to 15 knots
Floating objects	0 knots

The node is given 6 states and the following conditional distribution:

Speed	7.5 knots			15 knots		
State	**Large vessel**	**Small vessel**	**Floating object**	**Large vessel**	**Small vessel**	**Floating object**
5 knot	1 / 10	1 / 6	2 / 3	1 / 24	1 / 15	1 / 6
10 knot	2 / 10	2 / 6	1 / 3	2 / 24	2 / 15	2 / 6
15 knot	4 / 10	2 / 6	0	4 / 24	3 / 15	3 / 6
20 knot	3 / 10	1 / 6	0	7 / 24	3 / 15	0
25 knot	0	0	0	6 / 24	2 / 15	0
30 knot	0	0	0	4 / 24	1 / 15	0

The applied modelling assures that the majority of collision courses will be head-on.

Visual time and Radar time

Both visual time and radar time defines the time the given object will be visible. The assigned conditional distribution is identical for both nodes and both nodes are therefore described here. The node is defined conditional on the relative speed of the object and the distance to the object. It is assumed that the major parts of the collision candidates are met head on.

The object relative speed varies from 5 to 30 knots and the distance from 0 to 30 km. This implies that the visual time will be in the range of 0 to 140 minutes. In the modelling the node is given 45 states in the interval from 0 to 22 minutes, divided into intervals of 0.5 minute. In the modelling the time interval of interest is truncated at 22 minutes wherefore all objects being visible more than 22 minutes are defined to be visible only 22 minutes. This truncation has negligible impact on the analysis. The node is purely mathematical and serves only to transform the distance and relative speed into a time period.

Traffic intensity

The node describes the mixed ratio of the effect of traffic intensity and confinement of area. The node is modelled by the states: “Low”, “Medium”, and “High”. The definition of these states is vague and may therefore be the subject of improvement if more detailed information becomes available. But it is important to note that even if solo watch keeping only can be allowed in situations with low ship traffic then there will always be a variation of the intensity of “low ship traffic”. The assigned probability distribution is:

State	**Probability**
Low	0.70
Medium	0.29
High	0.01

Manoeuvring time

The manoeuvring time describes the required minimum time for performing an evasive manoeuvre. The manoeuvring time is most easily evaluated in terms of required number of vessel lengths for performing the evasive manoeuvre since the manoeuvrability will be dependent on the vessel length. Figure 3 below shows for different traffic intensities the probability density function for number of vessel lengths required for performing the evasive manoeuvre.

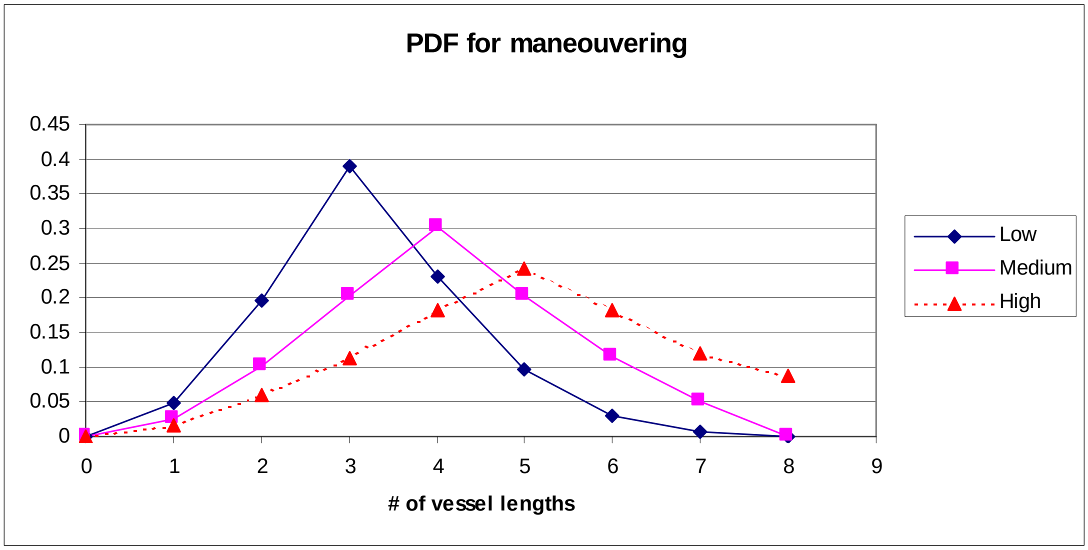


Figure 3: *Probability density functions for the number of vessel length required in order to perform an evasive manoeuvre.*

The length of the considered vessel is 200 m and given the vessel speed the time for manoeuvring is easily calculated. The node is discretised into 14 states, which are 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6, 6.5, and 7 minutes.

Time for visual and Time for radar

The nodes "Time for visual" and "Time for radar" are identical and purely mathematical. The node simply subtracts the manoeuvring time from the visual time and thereby gives the time left for performing the detection.

Other alarms

The node "Other alarms" describes the occurrence of other alarms during a watch that requires the attention of the OOW. The node has the state "Yes" and "No" and the following probability distribution has been assigned:

State	**Probability**
Yes	0.1
No	0.9

OOW training

The study [3] evaluated the training level of several OOW. On the basis of the observations performed the following probability distribution have been assigned:

State	**Probability**
Low	0.02
Average	0.39
High	0.59

Stress level

The modelling of the stress level is purely subjective. The stress level is divided into the states "Low", "Medium", and "High", although not associated with a psychological definition the applied modelling accounts for the effect of the stress level. Special studies may refine the modelling of the stress. The node is dependent on both the OOW training level and the occurrence of other alarms. The following conditional probability density is assigned.

Training	**Low**		**Medium**		**High**	
Alarms	**Yes**	**No**	**Yes**	**No**	**Yes**	**No**
Low	2 / 10	2 / 10	2 / 10	4 / 10	5 / 10	7 / 10
Medium	4 / 10	6 / 10	6 / 10	3 / 10	3 / 10	2 / 10
High	4 / 10	2 / 10	2 / 10	3 / 10	2 / 10	1 / 10

OOW task

In the analysis the tasks of the OOW is divided into the following three tasks:

1. Looking at the world

2. Looking at the radar

3. Other duties

The tasks describe the primary task of the OOW. The node models the ability of the OOW to divide his attention between the different tasks. This ability is dependent on both the bridge type and the stress level. The following conditional probability has been assigned:

Bridge	Conventional			Solo watch-keeping		
Stress	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**
World	55 / 100	55 / 110	55 / 120	70 / 100	70 / 110	70 / 120
Radar	20 / 100	20 / 110	20 / 120	20 / 100	20 / 110	20 / 120
Other	25 / 100	35 / 110	45 / 120	10 / 100	20 / 110	30 / 120

In reference [3] the percentage of time spent on lookout duties and non-lookout duties were observed. These observations were made for both the conventional and the solo watch keeping bridge under conditions that are judged to cause low stress levels. It was observed that approximately 50% of the time were spent on lookout duties on the conventional bridge, and 75 % of the time on the bridge equipped for solo watch keeping. The applied modelling (55 % and 75 %, respectively) therefore slightly favours the conventional bridge. The observation in [3] does not cover the time spent on looking at the radar and time spent on other duties. The assigned probabilities for these tasks are therefore assessed subjectively, although it has been assumed that the fraction of time spent on looking at the radar are identical for the two bridge types. The influence of higher stress levels is assumed to imply that more time is spend on other duties than the primary duties of the OOW.

Alarm transfer

A bridge safety system is used to ensure that an alert officer is present on the bridge this system is only present for the bridge allowing for solo watch-keeping and is modelled with three states: 5 minutes and 10 minutes interval, and none. The bridge safety system is required to be connected to an alarm transfer system. The alarm transfer system has reportedly in [1] a mean failure rate during a watch of $2.4 \cdot 10^{-5}$. The remaining probability ($1-2.4 \cdot 10^{-5}$) is divided uniformly between the 5 and the 10 minutes setting interval.

It is noted that the present study does not include a collision transfer system.

Looking frequency and Radar frequency

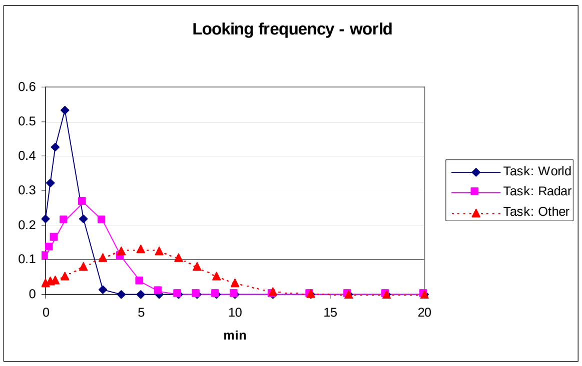
Both the looking frequency and the radar frequency is defined as the time between completions of full screening (and interpretation) of either the sea surface or the radar. The looking frequency will be dependent on the task of the OOW which are “Looking at the world”, “Looking at the radar”, and “Other duties”. The OOW being engaged in a different task than, for instance, looking at the world does not imply that the OOW does not look at the world. It implies that it will take the OOW longer time before a complete screening and interpretation has been completed.

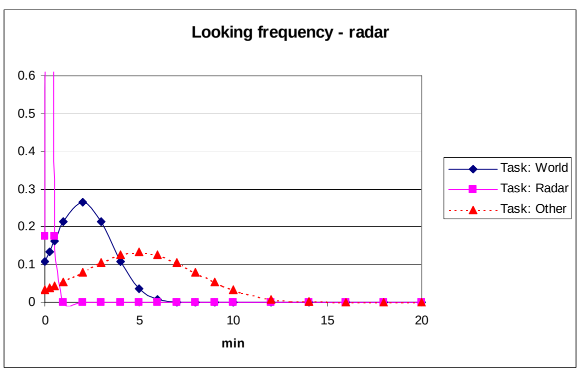
The modelling of the looking frequencies is illustrated in the figures below.

Figure 4: *Probability density functions for the world and radar looking frequencies, respectively.*

The mean frequencies are:

Task	Lookout mean frequency	Radar mean frequency
Looking at world	1 min	2 min
Looking at radar	2 min	0.25 min
Other duties	5 min	5 min





From the above it is seen that the duration of radar screening in average is 15 seconds. If an alarm transfer system is present, then all the above-defined distribution for looking frequencies are truncated at the time interval defined by the setting of the "Alarm transfer system".

Both nodes are discretised into 17 states, which are 0.25, 0.625, 1.25, 2, 3, 4, 5, 6, 7, 8, 9, 10.5, 12, 14, 16, 18, and 20 minutes. The probability of being in one of the intervals is calculated on the basis of the probability distributions shown in the figures above.

OOW visual and OOW radar

The nodes “OOW visual” and “OOW radar” defines whether the OOW is able to detect the object within the given time period as defined by the node “Time for visual” and “Time for radar” given a specified looking or radar frequency. As mentioned, the looking frequency models the time duration of one scanning of the sea surface, but one such scanning does not assure that the object surely will be identified. The probability of detecting the object within a given time period is calculated under the assumption that the scanning sequence follows a Poisson process, that is, the duration of consecutive scans are independent. The probability of detecting an object within a time period T given the frequency λ thereby becomes:

$$P[\text{detect}] = 1 - \exp(-\lambda T)$$

OOW acts

The node has the states “Yes” and “No”, and represents an OR-gate. The OOW is assumed to act if he either performs a visual detection or radar detection.

Bayesian Network for a conventional bridge

This section extends the formulated basic network to cover a conventional bridge. The Bayesian Network for the conventional bridge is established by adding the effect of the rating lookout during watch keeping at night. Both a rating lookout and the OOW could, in principle, detect the object by means of lookout and radar. However, a rating lookout is not competent to interpret the radar and the rating is therefore not allowed to keep lookout by looking at the radar. The presence of a rating lookout therefore only influences the visual detection. The Bayesian network modelling the watch keeping of the conventional bridge layout is thereby established by duplicating the visual detection part of the network. If the visibility during daytime becomes too low to assure safe ship operation, then the OOW will call a rating lookout to the bridge to assist the watch keeping. The resulting Bayesian Network is shown below.

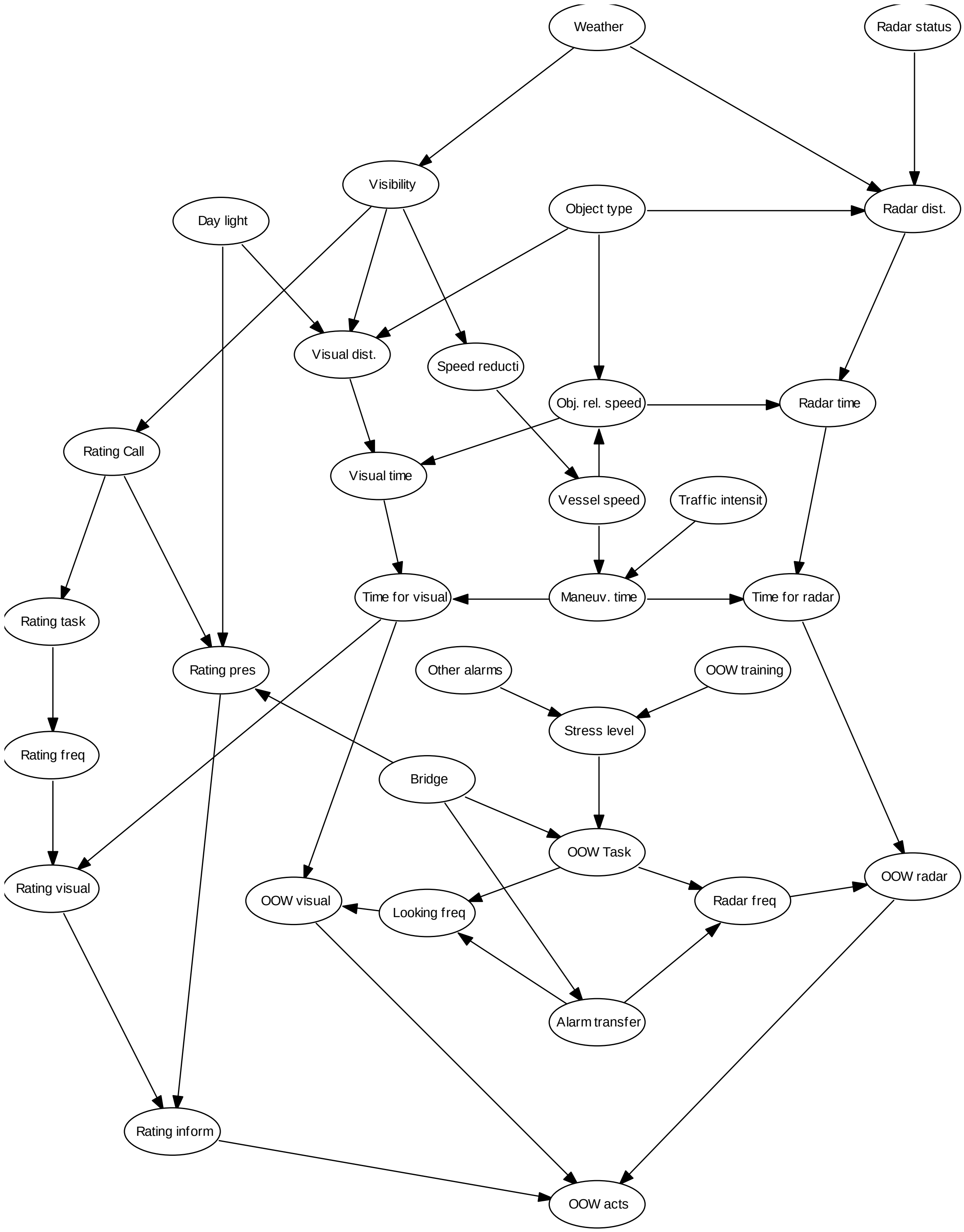


Figure 5: *Bayesian Network for watch keeping on a conventional bridge.*

Rating Call

The node describes whether or not the rating will be called (or be present) conditional on the conditions of the visibility during daylight. The node "Rating call" contains the states "Yes" and "No". It is assumed that the rating will be called only when the visibility is less than 1.5 km. If the visibility is larger then he will never be called. The assigned conditional probability density matrix is for the low visibility range given below:

Visibility	**0.25 km**	**0.5 km**	**0.75 km**	**1.0 km**	**1.25 km**	**1.5 km**
Yes	1	2 / 3	1 / 2	1 / 6	1 / 20	0
No	0	1 / 3	1 / 2	5 / 6	19 /20	1

Rating task

The node "Rating task" describes the tasks of the rating. These are "Watch" and "Others". On the basis of the observations made in reference [3] the rating is engaged in other activities 20% of the time. If the rating has been called to the bridge because of low visibility or if low visibility occurs during night then it is assumed that he will be engaged in other activities only 5% of the time. This modelling reflects that the rating will be more alert because of the low visibility.

Rating frequency

The rating is assumed to perform his lookout duty just as qualified as the OOW. The frequency with which the rating lookout scans the sea surface thereby becomes identical to the looking frequency of the OOW.

Rating visual

The node "Rating visual" is modelled identical to the node "OOW visual".

Rating present

The rating will only be present on the bridge during night or if he has been called because of low visibility. The node is also an auxiliary node since the basic network contains information of both the conventional bridge and the solo watch keeping bridge. The node is in state "Yes" if the bridge type is a conventional bridge and the watch is during night or the rating has been called because of low visibility. For all other the cases the node is in state "No".

Rating inform

The node "Rating inform" describes whether the rating will inform the OOW in the case that he detects an object. The node has the states "Yes" and "No", and it is assumed that if the rating detects an object then he will inform the OOW with the probability 0.9. If he does not detect the object, then he, of course, will not be able to inform the OOW. It is assumed that if the rating informs the OOW then the OOW will act.

Analysis of the conventional bridge

This section describes the results of the analysis of the conventional bridge. First we present a set of directly available results from the model. Afterwards a verification of the model is performed by comparison to observed results. In the analysis that follows the probability of the conventional bridge is set to one, and the probability of the solo watch keeping bridge is zero.

The probability of the OOW not acting in time is found to be 0.00270. This probability is calculated for the case of a rating lookout being present during darkness and in cases of low visibility. By conditioning on the node "Daylight" is in the state "Darkness" the probability of the OOW not acting decreases to 0.00209, whereas during daylight this probability is 0.00330. These values are summarised in the table below

Case	P[OOW not acting]
Day and night	0.00270
Daylight	0.00330
Darkness	0.00209

From this it is seen that the rating contributes significantly to the overall safety of the vessel having the conventional bridge system. We may quantify the effect of the presence a rating lookout on the system by calculating the probability of the OOW not acting conditional on the rating lookout not being present on the bridge. For a daylight situation the probability becomes 0.00331 whereas during darkness the probability becomes 0.00356. It is seen that the effect of a rating lookout being present during darkness on the conventional bridge decreases the probability of the OOW not acting by more than 40 %. The effect of the rating lookout being present on a bridge with the conventional bridge layout therefore has a significant impact on the ship safety. It is also seen that the effect of calling a rating lookout in the case of low visibility during daylight has no impact on the ship safety. Finally, from inspection of the node "Rating Call" we find that a rating is called to the bridge 2.3% of the time because of low visibility.

In reference [3] observation on the watch keeping on a traditional bridge were performed under good weather conditions. It was found that there were no significant difference between the daylight and the night situation. If we condition on good weather in the Bayesian Network and calculates the probability of the OOW not acting we find for the day and night situation 0.00172, for the daylight situation 0.00224, and for the darkness situation 0.00120. Thus, the model identifies a difference between the daylight and night situation, but the difference is small and it is doubtful whether it is possible to detect such small differences by observations.

A so-called max-propagation may used to identify the most probable state of the nodes in the case of the OOW not acting in time. Performing this analysis for the night situation results in the following observations.

Both the OOW and the rating will be looking at the world. Both the rating and the OOW will be performing this duty with a frequency of 1.25 minutes. The condition of weather is good, and the type of object with which the vessel is on collision course is a floating object. The most probable required time for manoeuvring is 1.25 minutes (with 1 minutes being more likely than 2 minutes).

The most probable state of the visual time of the object is 0.5 minutes, which reflects that the most probable object is a floating object.

From the max propagation performed above we may conclude that a collision will most probably occur with a floating object. The next step in the evaluation of the established network is therefore to evaluate the probability of the OOW not acting conditional on the object with which the vessel is on collision course. The table below gives this probability.

Object	**P[OOW not acting] (Day and night**	**P[OOW not acting] (Daylight)**	**P[OOW not acting] (Darkness)**
Large vessel	0.00193	0.00264	0.00122
Small vessel	0.00191	0.00267	0.00116
Floating object	0.773	0.649	0.898

It is seen that the model predicts that a floating object during darkness will not be detected in almost 90% of the cases. During daytime the probability of not detecting a floating object in time is calculated to be 0.649. From the table it is also seen that the probability of the OOW not detecting a large or a small vessel does not differ significantly.

It is illustrative to perform a max propagation for the case when the OOW not acting when the vessel is on collision course with a large vessel.

During the darkness situation when the rating is present the most probable condition for the weather is rain or fog. The visibility will in this case most probably be in the range from 0.250 to 0.5 kilometres. The most likely stages of the radar range will be 30 km. Both the rating and the OOW will be performing lookout duty, but it is more likely for the OOW to be engaged in other activities than looking at the radar. The stress level of the OOW will be low.

During daylight, where the rating lookout is not present, the most likely condition of the weather is good with high visibility and large radar range. The OOW will most likely be engaged in other activities causing the most probable looking frequency on both the radar and the world to be 7 minutes.

Verification of model

There has not been found much data that may be used for verification of the modelling. Large part of the observations made in [3] form the basis for the applied modelling in the present study. Therefore only a few of these observations are useable for a comparison. It was observed in [3] that when a rating lookout was not present lookout lapses longer than 10 minutes occurred 0.2% of the time. We may compare this figure to the marginal distribution of the node “Looking freq.” in the Bayesian Network. By summing all probabilities in this node that are larger than 10 minutes we obtain 0.29%. The values are comparable in magnitude.

The second part of the verification study relates to the dependence of risk of collision on visibility. In the study by Fujii [7] the number of traffic accidents in major straits in Japan and the associated visibility were registered from 1966 to 1971. In [7] the relationship between visual range and degree of risk was evaluated and it was found that the risk was approximately proportional to $1/r^{1.6}$, where r is the visibility. In the establishment of this relationship the low traffic volume in low visibility was taken into account. In the Bayesian Network presented here, no effects of reduced traffic volume in low visibility are included. We may, however, calculate the probability of the OOW not acting conditional on a given visibility and conditional on the collision objects is either a large or a small vessel, only. The figure is shown below.

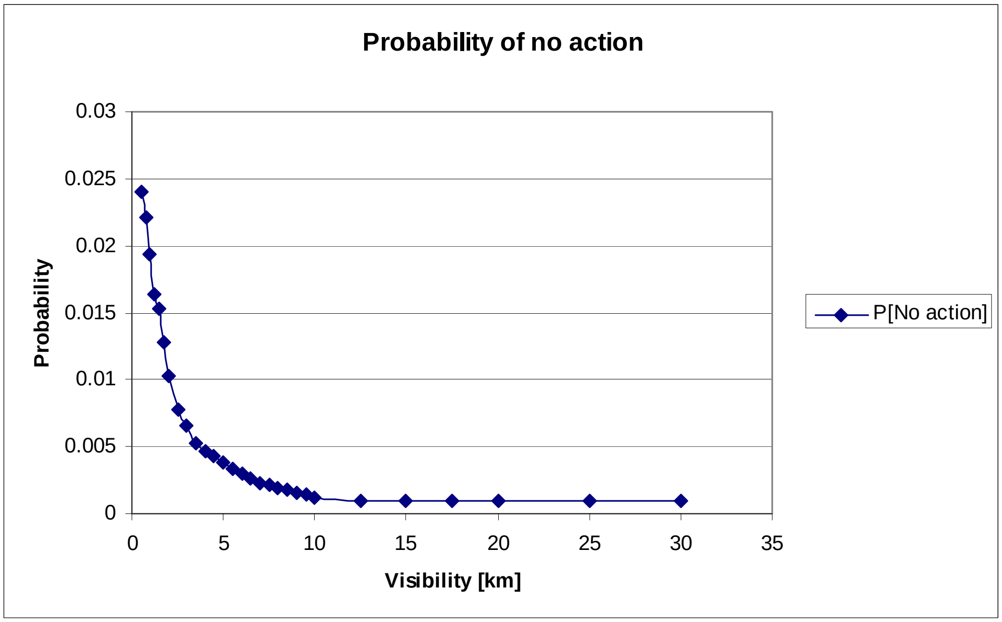


Figure 6: *Calculated probability density function for no action of the OOW as a function of the meteorological visibility.*

By establishing a double logarithmic plot of the probability of the OOW not acting conditional on a given visibility the sought relationship is found. The figure is shown below.

The figure shows the obtained double logarithmic plot for the entire visibility range. The linear regression of the dependency is shown in the figures. It is seen that for the entire range we obtain the relationship between visual range and degree of risk is approximately proportional to $1/r^{1.1}$ for the entire visibility range. We see that the proportionality factor is comparable, but smaller than that given in [7]. The lower factor is to be expected since radar technology has improved during the past three decades. The performance of the radar is especially important for the low visibility range since a visual detection in time is very unlikely, whereas it is very likely that the radar will detect an object in low visibility. The impact of modern radar technology is therefore that the probability of not acting in time in the low visibility range decreases, whereas the probability in high visibility remains almost unchanged. If the radar performance is decreased by assigning a higher probability of the radar to be in a fault situation, then the present model will predict a higher proportionality factor. Some of the differences in this comparison may also reflect the difference between Japan and Northern Europe in the causes (fog or heavy rain) for low visibility.

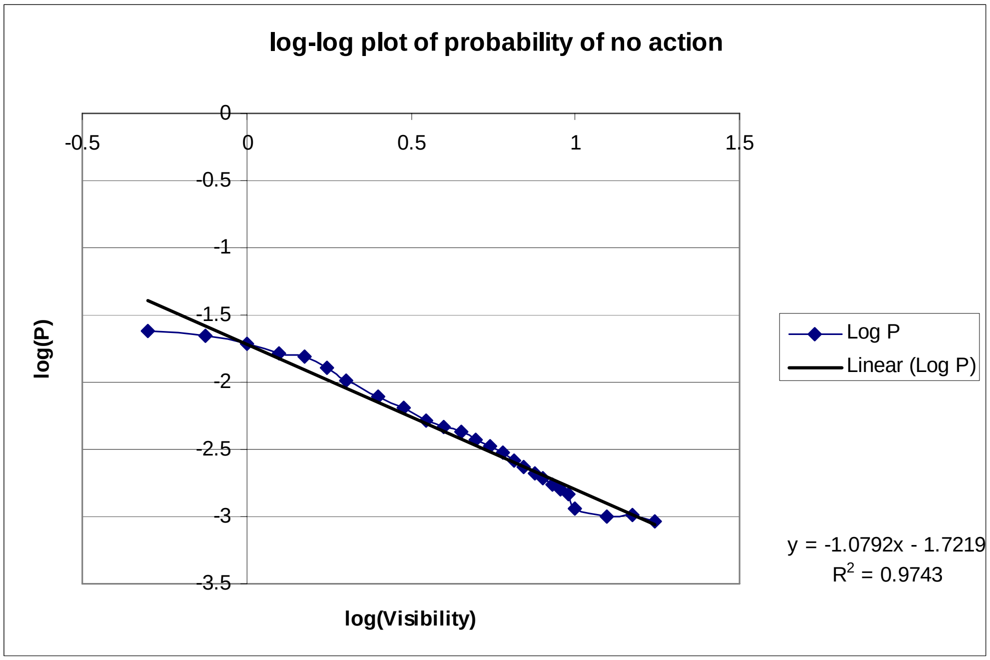


Figure 7: *Double logarithmic plot calculated probability density function for no action of the OOW as a function of the meteorological visibility.*

Bayesian Network for a solo watch keeping bridge

This section extends the formulated basic network to cover a bridge equipped for solo watch keeping. The Bayesian Network for the solo watch keeping bridge is established by adding the effect of the backup when called. Since the called backup is assumed to be a qualified officer, both the OOW and the backup, if present, may detect the object by means of lookout and radar. The presence of a backup therefore influences both the visual detection and the radar detection. The backup will by judgement of the OOW be called in critical situations when rough weather, low visibility, or high traffic density requires this in order to continue safe vessel operation. The Bayesian network modelling the watch keeping of the solo watch keeping bridge layout is shown in Figure 8.

Basically, the Bayesian Network for solo watch keeping is established almost only by duplicating the lower part (below “Time for visual” and “Time for radar”) of the previously formulated basic network. This is because the backup is as qualified as the OOW and therefore may perform the same tasks as the OOW. If the backup detects the object (either visually or by use of the radar), with which the vessel is on collision course, then he will inform the OOW who then will act. The OOW must, however, first have decided that external conditions require a backup to be present on the bridge. The backup may either be called because of bad weather, because of low visibility, or because of high traffic density. Below we describe the new introduced nodes in the network modelling the solo watch keeping bridge. It is noted that we have not included backup calls due to technical failures.

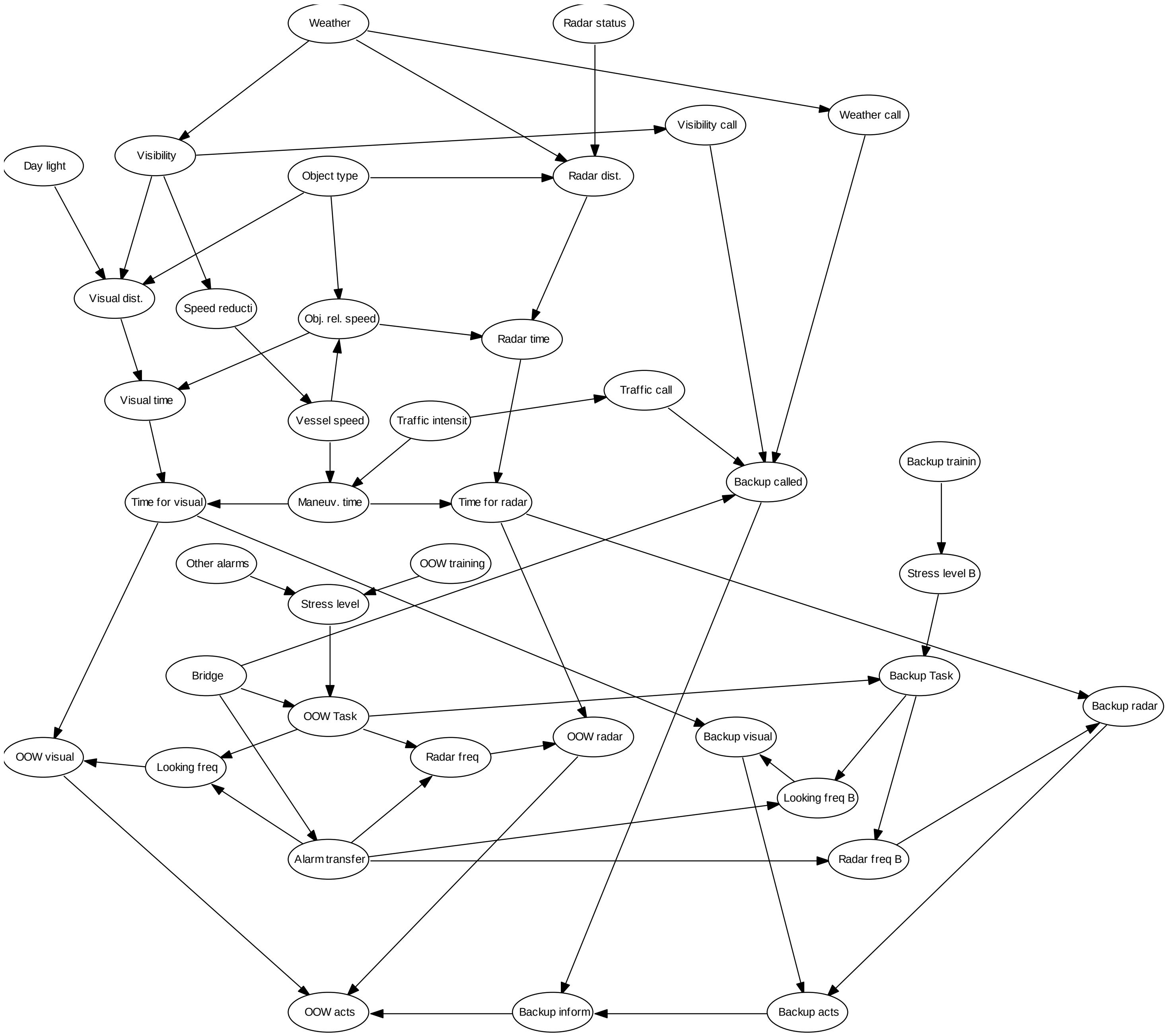


Figure 8: *Bayesian Network for watch keeping on a bridge equipped for solo watch keeping.*

Weather call

The node describes whether or not the backup will be called (or be present) conditional on the actual weather conditions. The node "Weather call" contains the states "Yes" and "No". The assigned conditional probability density matrix is given below:

Weather	Good	Storm	Rain	Snow	Fog
Yes	0	1 / 50	0	0	0
No	1	49 / 50	1	1	1

It is seen that it is assumed that the backup will be called only in case of a storm, that is when Beaufort is larger than 6. The backup will, however, also be called in other weather conditions, but these cases will be related to visibility, which are described in the following.

Visibility call

The node describes whether or not the backup will be called (or be present) conditional on the conditions of the visibility. The node "Visibility call" contains the states "Yes" and "No". It is assumed that the backup only will be called when the visibility is less than 1.5 km. If the visibility is larger then he will never be called. The assigned conditional probability density matrix is for the low visibility range given below:

Visibility	0.25 km	0.5 km	0.75 km	1.0 km	1.25 km	1.5 km
Yes	1	2 / 3	1 / 2	1 / 6	1 / 20	0
No	0	1 / 3	1 / 2	5 / 6	19 /20	1

This modelling is identical to the earlier modelling of the node "Rating call".

Traffic call

The node describes whether or not the backup will be called (or be present) conditional on the traffic density. The node "Traffic call" contains the states "Yes" and "No". The assigned conditional probability density matrix is given below:

Traffic intensity	Low	Medium	High
Yes	0	1 / 1000	1 / 50
No	1	999 /1000	49 / 50

It is seen that a relatively low probability is assigned to the backup being called due to the traffic situation. This is because we only consider relatively low traffic densities as previously discussed.

Backup called

The name of the node “Backup called” is somewhat misleading since the node does not model the actual calling situation, but rather whether or not a backup will be present under the given conditions. It would be a practicable impossible situation to model the specific case of the actual calling of a backup. Modelling this would require modelling of how the joint weather and visibility process gradually would be changing and inclusion of uncertain threshold limits for the calling to take place. Aiming at such a modelling is far beyond the scope of the present study.

The node “Backup called” has the states “Yes” and “No”. The node is an OR node defining that the backup is called if a weather call, a visibility call, or a traffic call has taken place.

Backup training

The training level of the backup is assumed identical to that of the OOW. The modelling of the node is therefore identical to the modelling of the node “OOW training”.

Stress level Backup

The stress level of the backup is modelled as the stress level of the OOW when no other alarms are present. A backup will, of course, only be called in critical situations. It is, however, assumed that the backup will fell less stressful than compared to situations when alarms are present. This since both the OOW and the backup will be able to discuss the critical situation.

Backup task

It must be assumed that there will be some co-ordination between the task of the backup and the task of the OOW. If the OOW is concentrated on the radar, then it is more likely that the backup will concentrate on the “world” or other duties than also the radar. The following conditional probability density has been assigned conditional on the task of the OOW:

OOW Task	**World**		
Stress level Backup	**Low**	**Medium**	**High**
World	70 / 100	70 / 110	70 / 120
Radar	20 / 100	20 / 110	20 / 120
Other	10 / 100	20 / 110	30 / 120

OOW Task	Radar		
Stress level Backup	**Low**	**Medium**	**High**
World	85 / 100	85 / 110	85 / 120
Radar	5 / 100	5 / 110	5 / 120
Other	10 / 100	20 / 110	30 / 120

OOW Task	Other		
Stress level Backup	**Low**	**Medium**	**High**
World	75 / 100	75 / 110	75 / 120
Radar	20 / 100	20 / 110	20 / 120
Other	5 / 100	10 / 110	15 / 120

Looking frequency Backup

The node is identical to the node “Looking freq.”

Radar frequency Backup

The node is identical to the node “Radar freq.”

Backup visual

The node is identical to the node “OOW visual”

Backup radar

The node is identical to the node “OOW radar”

Backup acts

The backup will act if he either detect visually or by the radar

Backup inform

The node is a logical AND node. If the backup is present and he detects, then he will inform the OOW, which then in turn will act.

Analysis of the solo watch keeping bridge

This section describes the results of the analysis of the solo watch keeping bridge. First we present a set of results directly available from the model. Afterwards a verification of the model is performed by comparison to observed results. In the analysis that follows the probability of the solo watch keeping bridge is set to one.

The probability of the OOW not acting in time is found to be 0.00155. This probability is calculated for the case of both daylight and darkness. By conditioning on that the node "Daylight" is in the state "Darkness" the probability of the OOW not acting slightly increases to 0.00169, whereas the probability in the case of daylight is 0.00141. This result agrees well with the observation made in reference [3] where no significant difference between the daylight and the night situation was found. The results are summarised in the table below:

Case	P[OOW not acting]
Day and night	0.00155
Daylight	0.00141
Darkness	0.00169

By inspecting the marginal distribution for the node "Backup called" it is found that the backup will be present on the bridge 2.4% of the time. By conditioning on the weather being in the state "Good" it is found that the backup will be on the bridge 0.049% of the time. Performing a max propagation leads to the same observations as obtained for the conventional bridge.

Comparison of the conventional bridge and the solo watch keeping bridge

In this section we shall compare a selected set of results from the analysis of the conventional bridge and the solo watch keeping bridge. For all analysed cases the probability of the OOW not acting is calculated. For each comparative condition the probability of the OOW not acting has been calculated for a "Day and night", a "Daylight", and a "Darkness" condition.

P[OOW not acting] :	All weather conditions – all objects	
Case	**Conventional bridge**	**Solo Watch bridge**
Day and night	0.00270	0.00155
Daylight	0.00330	0.00141
Darkness	0.00209	0.00169

From the above table it is seen that the day and night probability of the OOW not acting is significantly lower (about 40%) for the bridge equipped for solo watch keeping compared to the conventional bridge. It is also seen that the conventional bridge type during darkness – when a rating lookout is present – is almost as safe as the bridge equipped for solo watch keeping.

P[OOW not acting] :	All weather conditions – Large vessels	
Case	**Conventional bridge**	**Solo Watch bridge**
Day and night	0.00193	0.000778
Daylight	0.00264	0.000784
Darkness	0.00122	0.000773

The above table gives the probability of the OOW not acting in the case where the collision object is a "Large vessel". Again it is seen that the bridge equipped for solo watch keeping is much safer (about 60%) than the conventional bridge.

In an evaluation of the obtained probability levels by the applied modelling we may calculate the probability that the object is a "Large vessel" and that the considered vessels collide. We may calculate this probability in two limiting cases. The probability of the two OOW's on the two vessels may either be fully dependent or fully independent (being the most likely).

For the fully independent case the ship-ship collision probabilities becomes:

	Conventional	**Solo Watch**
Conventional	$3.72 \cdot 10^{-6}$	$1.50 \cdot 10^{-6}$
Solo Watch	$1.50 \cdot 10^{-6}$	$6.05 \cdot 10^{-7}$

For the fully dependent case the ship-ship collision probabilities becomes:

	Conventional	**Solo Watch**
Conventional	$1.93 \cdot 10^{-3}$	$1.93 \cdot 10^{-3}$
Solo Watch	$1.93 \cdot 10^{-3}$	$7.78 \cdot 10^{-4}$

Comparing to the causation factors observed by Fujii [7] these values should be in the range from $1.2 \cdot 10^{-4}$ to $5.0 \cdot 10^{-5}$. We can therefore conclude that the applied modelling seems to result in probability levels of the correct order of magnitude.

P[OOW not acting] :	All weather conditions – Small vessels	
Case	**Conventional bridge**	**Solo Watch bridge**
Day and night	0.00192	0.000788
Daylight	0.00267	0.000794
Darkness	0.00116	0.000783

The above table gives the probability of the OOW not acting in the case where the collision object is a "Small vessel". Again it is seen that the solo watch keeping bridge is 60% safer than the conventional bridge. It is also seen that the probability of the OOW not acting given that the collision object is a "Small vessel" is marginally lower than in the case of a "Large vessel". This is because the travelling speed of the "Large vessel" in general is larger than the travelling speed of the "Small vessel". This implies that the relative speed between the considered vessel and the "Large vessel" becomes larger compared to the "Small vessel" and consequently there is shorter time to detect the "Large vessel" than the "Small vessel". An effect that counteracts the effect of the travelling speed is the visual distance of the two objects. The visual distance of the small vessel in general is smaller than for a large vessel.

P[OOW not acting] :	All weather conditions – Floating objects	
Case	**Conventional bridge**	**Solo Watch bridge**
Day and night	0.773	0.768
Daylight	0.649	0.620
Darkness	0.898	0.915

In the table above is given the probability of the OOW not acting given that the collision object is a "Floating object". It is seen that there is a very high probability of not detecting a "Floating object". It is also seen that the probability of the OOW not acting is almost identical for the solo watch keeping bridge and the conventional bridge. "Floating object" can only be detected visually, not by the radar. It is therefore also seen that a floating object is detected slightly better during darkness on the conventional bridge, where a rating lookout is present than on the solo watch keeping bridge.

The above comparisons were made for all weather conditions and thereby also low visibility ranges. If we compare the two systems in "Good weather" conditions only, implying visibility ranges larger than 10 kilometres, the following is found:

P[OOW not acting] :	Good weather – All objects	
Case	**Conventional bridge**	**Solo Watch bridge**
Day and night	0.00172	0.00127
Daylight	0.00224	0.00112
Darkness	0.00120	0.00141

First it is seen that the probability of the OOW not acting is almost 2 times lower than the all weather condition. It is also seen that the probability of the OOW not acting is 25% lower for the day and night situation for the solo watch keeping bridge compared to the conventional bridge. For the daylight situation, the bridge equipped for solo watch keeping is 50% safer than the conventional bridge. Moreover, it is seen that the probability of the OOW not acting during darkness is almost 20% higher than the conventional bridge system. There are several factors influencing this result. First, in the modelling of the node "OOW task" the probability of the OOW looking at the "World" was set to 55% in the case of the conventional bridge and 70% in the case of the solo watch keeping bridge. According to the observations in [3] these numbers should have been 50% for the conventional bridge and 75% for the solo watch keeping bridge. Our modelling therefore favours the conventional watch keeping bridge. We have applied this modelling since the node is relatively important for the results, and at the same time it is difficult to accurately access the time spend on the different duties. If we either increases the fraction of time spend on the "World" on the solo watch keeping bridge from 70% to 75% or decreases the time spend on the "World" on the conventional bridge form 55% to 50%, then the probabilities becomes almost identical. Consequently, if we assign the time fraction according to the observation, then the probability of the OOW not detecting becomes lower during darkness on the solo watch keeping bridge than on the conventional bridge.

By inspecting the above calculated probability levels, it is seen that the results obtained for the conventional bridge is highly dependent on the rating lookout being present during night (or present 80% of the time) on the bridge. If this not is the case, then the probability of the OOW not acting in good weather during darkness increases by a factor of 2 (to 0.00249) and becomes much larger than the above obtained result for the solo watch keeping bridge.

Concluding remarks

In the present report we have performed a comparative risk analysis study of a conventional bridge and a bridge equipped for solo watch keeping. The analysis is based on a Bayesian

Network modelling where the data entering the modelling to an as far as possible extend is from registered data (mainly from reference [3]). Wherever possible we have compared results to registered data and good agreement has been found.

On the basis of the results we can conclude that a solo watch keeping bridge is safer than the conventional bridge (approximately 40%). It is found, however, that the conventional bridge better identifies floating objects during darkness than on a solo watch keeping bridge. For both bridge types the probability of not detecting a floating object is very high and the impact of the difference in the two systems are therefore negligible.

All in all, from the present modelling we may conclude that the solo watch keeping bridge equipped with Graphic Position Display and alarm transfer system is safer than the conventional bridge without these features.

References

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[3] Schraagen, J.M.C.; Breda, van L. and Rasker, P.C.: Officer of the navigational Watch acting as the Sole Lookout during periods of darkness: Results of Empirical Evaluations. TNO Human Factors Research Institute, August 1997.

[4] Wikman, J. & Andersson, P.: Analysis of the Safety Levels With and without Sole Look-out in Periods of Darkness. MariTerm AB Report June 1997.

[5] IMO STW 27/9 Officer of the Navigational Watch Acting as the Sole Look-out in Periods of Darkness – Assessment of trial Results of Solo watch-keeping in Periods of Darkness. October, 1994.

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[8] Sparre, Agnes: "Wind, Visibility, Air temperature, Cloud amount, and Weather", Climatological Papers No. 8. Danish Meteorological Institute, Fyrskibsstatistik I, 1981.

[9] Statistical Yearbook, Volume 92, Danmarks Statistik, 1988

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Appendix A

Modelling of the Environment.

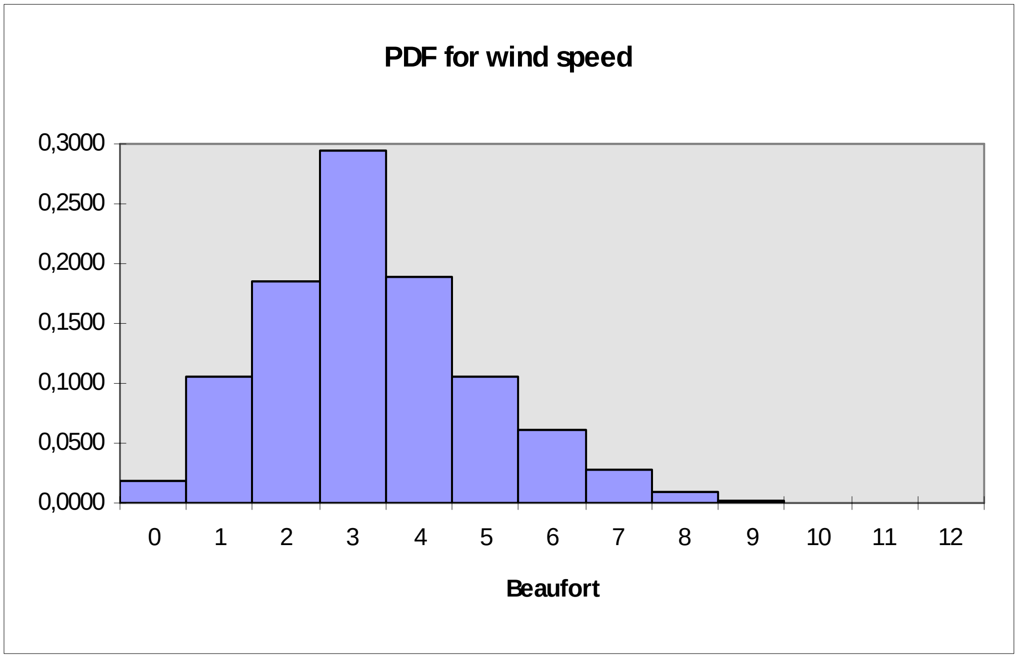
The visual sense supplies a major part of the information necessary for avoiding traffic accidents and fog impedes this channel of information, even though the invention of radar has removed the limitation to a considerable extend. Sparre [8] reports statistic of wind, visibility, air temperature, cloud amount, and weather recorded for 13 different light vessels located in Danish waters in the period from 1931 to 1960. Most of the light vessels have been located in inner Danish Water. Here we will only summarise the statistic for data recorded at the light vessel Vy1, since this vessel is located in the North Sea and is thereby judged to be more representative for the present study. More precisely, Vy1 was located approximately at 55^{o}23'N and 7^{o}36'E. Vy1 was not operating during the Second World War. Each day six observations have been made. The observation were performed at 4 a.m., 8 a.m., 12 noon, 4 p.m., 8 p.m., and 12 midnight C.E.T. (Danish time). Although [8] only reports limited information on the correlation between the recordings of weather and visibility, the data have been found relevant for the present study.

Wind is measured in Beaufort, and [8] give the following relationship to wind speed in knots:

Knots	Beaufort
0	0
1-3	1
4-6	2
7-10	3
11-16	4
17-21	5
22-27	6
28-33	7
34-40	8
41-47	9
48-55	10
56-63	11
64-71	12

The probability density function for the wind speed is in [8] given on a monthly basis. Here we have established the probability density function for the annual wind speed:

Beaufort	**Frequency**
0	0,0180
1	0,1063
2	0,1848
3	0,2943
4	0,1897
5	0,1061
6	0,0609
7	0,0281
8	0,0090
9	0,0022
10	0,0006
11	0,0001
12	0,0000



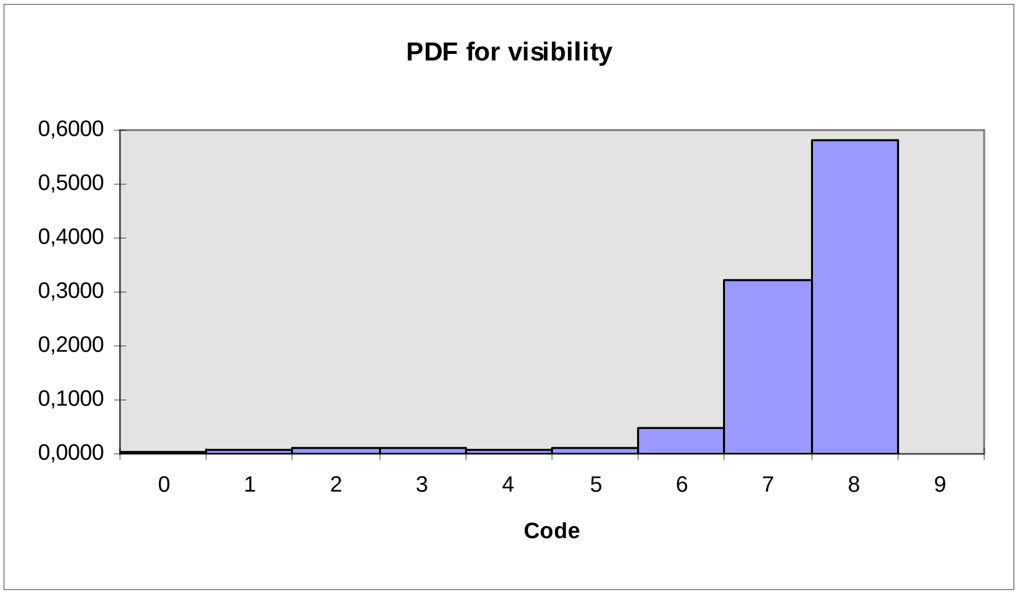
Visibility has been estimated since 1932 using the following scale:

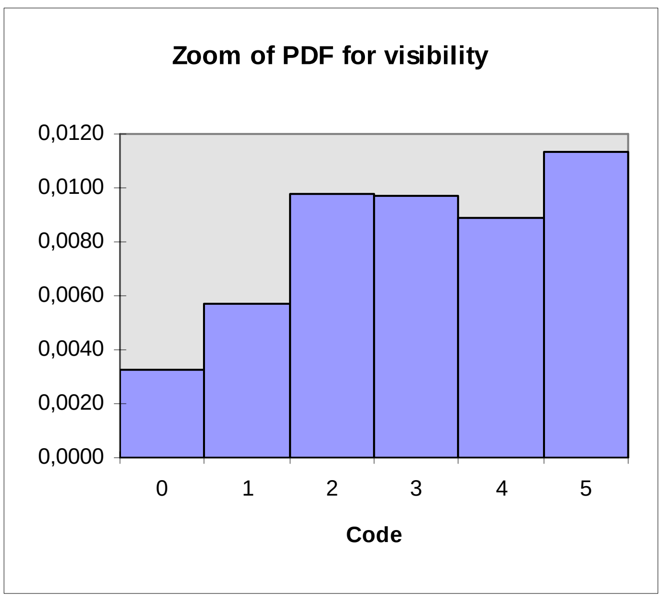
Code	Meaning	Objects visible
0	Extremely dense fog	Below 50 m
1	Dense fog	From 50 to 200 m
2	Fog	From 200 to 500 m
3	Moderate fog	From 500 to 0.5 nautical mile
4	Mist	From 0.5 to 1 nautical mile
5	Low visibility	From 1 to 2 nautical miles
6	Moderate visibility	From 2 to 5 nautical miles
7	Good visibility	From 5 to 10 nautical miles

8	Very good visibility	From 10 to 30 nautical miles
9	Excellent visibility	More than 30 nautical miles

It should be noted that visibility less than 0.5 nautical mile may occur for other reasons than due to fog, e.g. snow or heavy rain. The annual frequency distribution for visibility have been established from the monthly given basis:

Code	Frequency
0	0,0033
1	0,0057
2	0,0098
3	0,0097
4	0,0089
5	0,0113
6	0,0469
7	0,3229
8	0,5811
9	0,0004

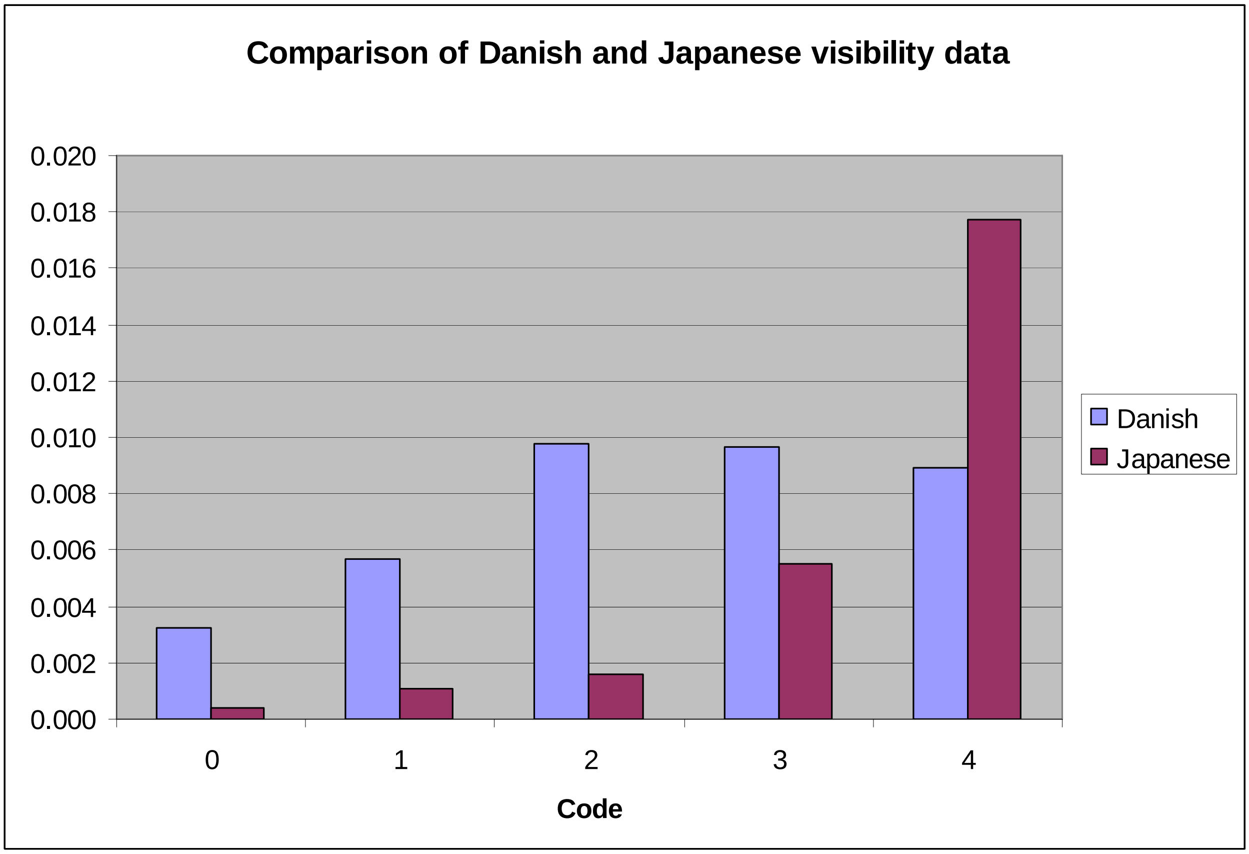




Fujii [7] has reported visibility ranges for the Japanese waters. To identify the frequency of the different visibility ranges, [7] has studied Lighthouse data for six different straits in Japan and related these to the visibility ranges of a referenced study by Nishikura. The average frequency data and the associated visibility ranges are given in the table below.

Code	Visibility	Frequency Japan [%]
0	0 – 50 m	0.04
1	50 – 200 m	0.11
2	200 – 500 m	0.16
3	0.5 – 1 km	0.55
4	1 – 2 km	1.77
5	2 – 4 km	5.18
6	4 – 10 km	19.65
7	10 – 20 km	23.25
8	20 – infinity (40) km	49.28

It is seen that the code definition of these visibility ranges (at least form code zero to code four) are in agreement with the Danish study. Below the Danish and the Japanese visibility ranges are compared.

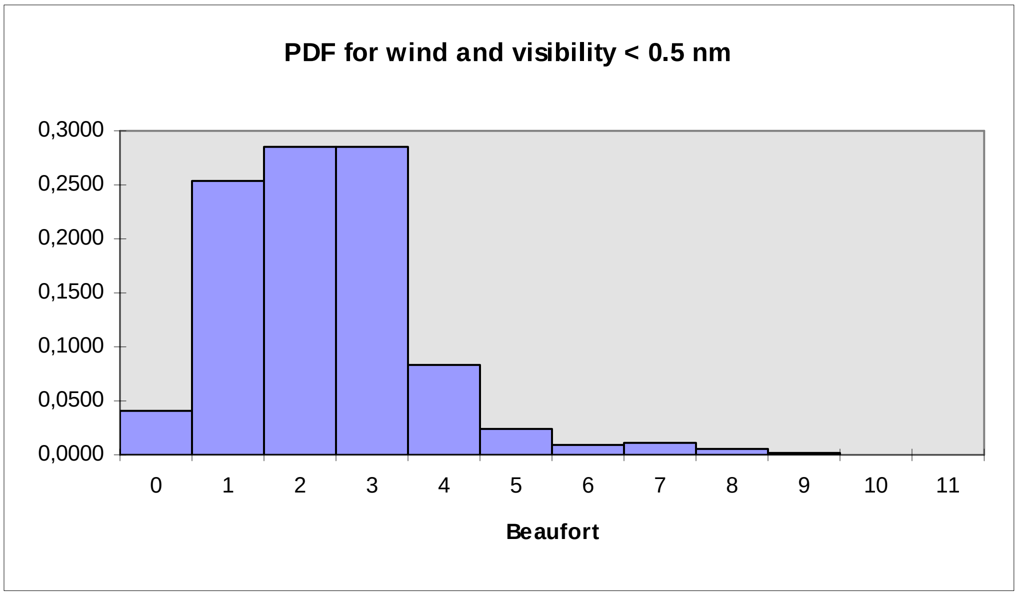


The above comparison indicates that there is a higher probability of thick and dense fog in Danish waters than in the reported Japanese Straits.

Ref. [8] also defines the distribution for wind forces given the visibility is less than 1 km (0.5 nautical mile). The annual distribution is given below.

Beaufort	**Frequency**
0	0,0401
1	0,2535
2	0,2847
3	0,2857
4	0,0840
5	0,0238

6	0,0091
7	0,0104
8	0,0054
9	0,0023
10	0,0009
11	0,0000

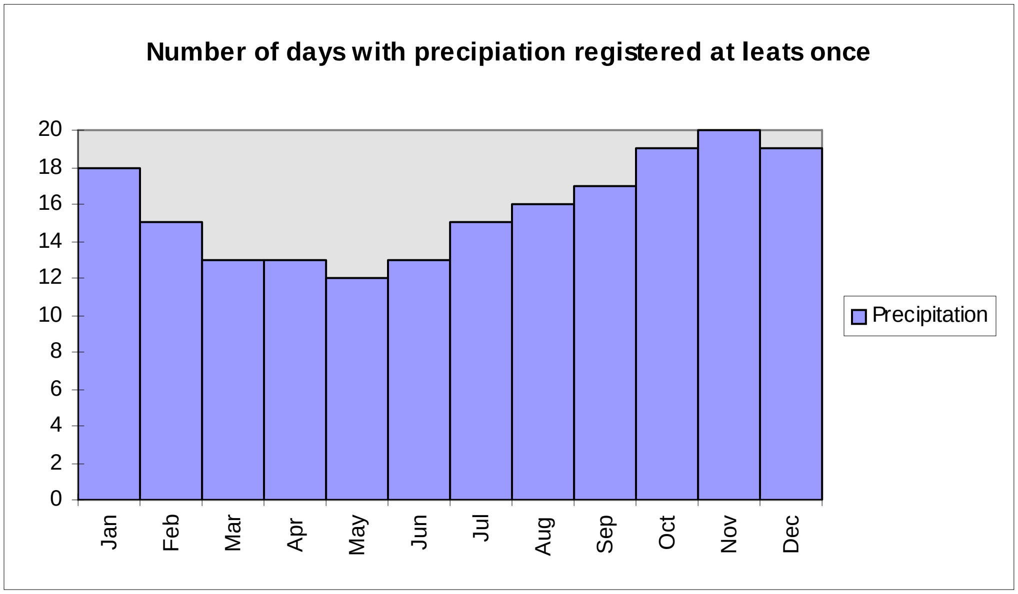


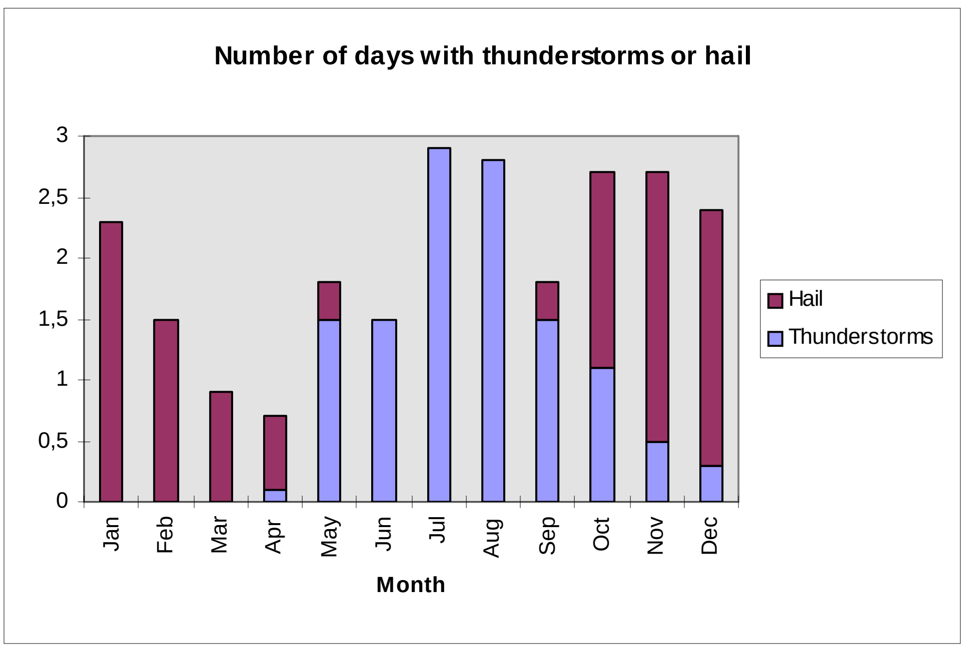
Air temperature has not been considered relevant for the present study.

Cloud amount was estimated in tenths, that is using a scale from 0 to 10 in which 0=cloudless sky, 1= 1/10 of the sky is covered with clouds, etc., up to 10=sky completely overcastted). The average cloud amount for the entire period is 6.79 having a standard deviation of 0.71. There has only been observed a minor variability over the hours of the day.

Weather was observed during the 24 hours, and a day with precipitation is one on which rain, sleet, snow or hail are observed at least once in the course of the day (which extends from 12 midnight to 12 midnight). The same applies to days with thunder and days with hail. It is understood that days with thunderstorms or hail are included in days with precipitation.

Month	Precipitation	Thunderstorms	Hail
Jan	18	0,0	2,3
Feb	15	0,0	1,5
Mar	13	0,0	0,9
Apr	13	0,1	0,6
May	12	1,5	0,3
Jun	13	1,5	0,0
Jul	15	2,9	0,0
Aug	16	2,8	0,0
Sep	17	1,5	0,3
Oct	19	1,1	1,6
Nov	20	0,5	2,2
Dec	19	0,3	2,1
Total	190	12,2	11,8
Average	15,83	1,017	0,983





Besides the above given conditional density function for wind speeds given the visibility is less than 1 km [8] does not specify any correlation between wind, visibility, and weather.

Description of nodes

Weather condition	**Days**
Summer days > 25C	10.2
Ice days and nights	23
Frosty days and nights	88
Fogy days and nights	67
Precipitation days or night	159
Days and nights with large precipitation	16
Days and nights with snow	25
Days and nights with wind speeds larger than 6 BF	10
Days or nights experiencing thunder	116
Days and nights with thunder	11.3

From [9] p. 9 1931-1960:

Summer days > 25C	10,2
Ice days and nights	23
Frosty days and nights	88
Fogy days and bights	67
Precipitation days and night	159
Days and nights with large precipitation	16
Days and nights with	25

snow	
Wind speeds larger than 6 BF	10
Days or nights experiencing thunder	116
Days and nights with thunder	11,3

Weather:

The following states are assumed relevant for modelling the weather - or rather for modelling the influence of weather on visibility and radar performance:

Weather type	**Number of days**
Good	327
Storm	14
Rain or snow	19
Heavy rain	0.5
Fog	4.5

The considered weather types and the associated number of days of occurrences are identified on the following basis:

Fog: It is assumed that fog causes visibility to be less than 1 km and that fog only may occur when the Beaufort number is between two and four. Assuming further that 75% of all visibility less than 1 km are due to fog, the probability of fog may be found by a summation over Beaufort wind speeds 2, 3, and 4, and subsequently multiplying this value by 0.75.

Rain and snow: The annual average number of days with rain from 1931 to 1960 is given in [9] as 16 days. The number of days with rain cannot be deduced from the Light vessel data [9] described in the previous section since that study registered occurrence of precipitation in any degree during the day. However, 16 days of rain appears to be reasonable by comparing to the

12.2 days of registered thunderstorms and 11.2 days of registered hail given in [8]. No data was found which defined the number of days with heavy snow. Ref. [8] indicates that snow in average is experienced 25 days of the year. It is assumed that heavy snow occurs 3 days of the year. In total, the modelling therefore assumes that rain or snow is experienced 19 days of the year.

Heavy rain: No data was found which defined the number of days with heavy rain. However, Ref. [8] report 12.2 days of registered thunderstorms and 11.2 days of registered hail. It is therefore assumed that heavy rain occur ½ a day of the year.

Good weather: Good weather is defined as weather with large visibility and wind speeds less than or equal to 6 Beaufort. The resulting number of days is extracted from [8] as the number of days with Beaufort Nos. less than or equal to 6 and subtracting days with rain, snow or fog. Good weather is present 327 days of the year.

Storm: Storm is defined as Beaufort wind speeds larger than or equal to 7. Storm is present 14.5 days of the year.

Visibility:

The node "Visibility" defines the probability distribution for the visibility conditional on the weather. As no study has been identified which defines the required basis, these distributions have been established on a subjective basis. As background material for the subjective assessment the marginal distribution for the visibility and some correlation between wind speeds and visibility. In the assignment of the conditional probability density functions it was required that the assigned marginal cumulative density function should represent the observed cumulative density function for the visibility. The assigned conditional probability density functions have been modelled as truncated Weibull distributions. The upper truncations limit of the visibility is 60 km, that is, in the modelling it is assumed that visibility larger than 60 km cannot occur. The truncation limit has only impact on the distribution for the visibility in good weather. The assumed distributions for visibility are given below.

For information conditional expected visibility for the different weather conditions are given below:

Weather	**Good**	**Storm**	**Rain/ snow**	**Heavy rain**	**Fog**
Expected visibility	28.9 km	6.8 km	4.0 km	0.45 km	0.45 km

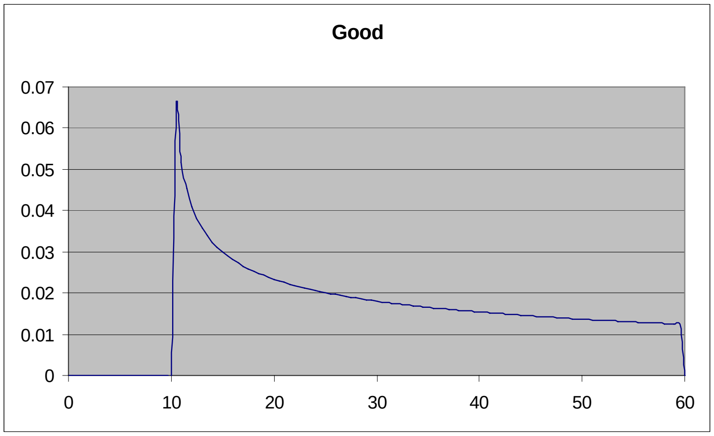
The parameters describing the obtained Weibull distributions are:

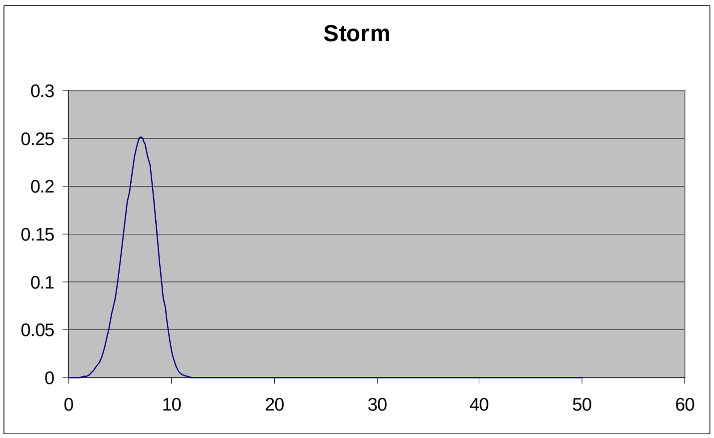
Weather	**Good**	**Storm**	**Rain / snow**	**Heavy rain**	**Fog**
α	0.01174	1.007E-04	0.4083	1.910	1.910
β	0.674	4.714	0.746	0.749	0.749
γ	10.0	0.40	0.10	0.0	0.0

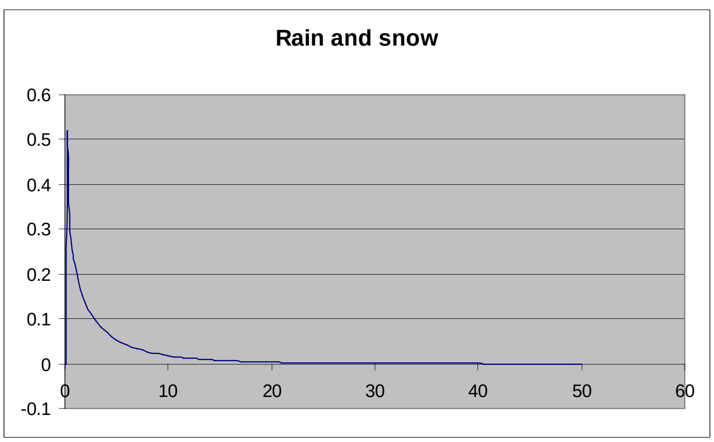
The format of the Weibull distribution is

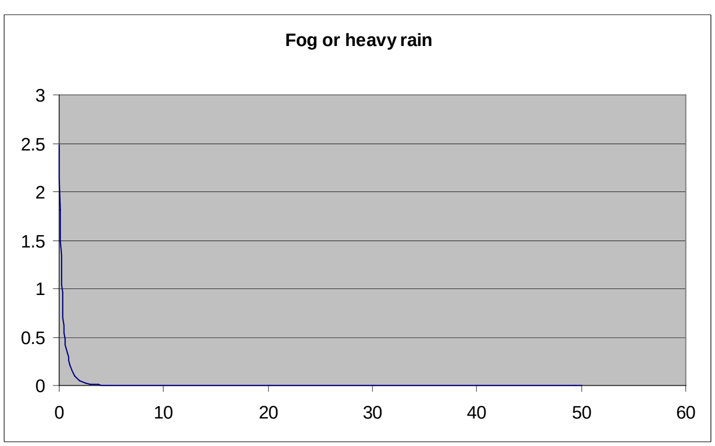
$$F(x) = 1 - \exp(-\alpha x^{\beta})$$

Figures for all visibility types are given below:


Good
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
10
20
30
40
50
60

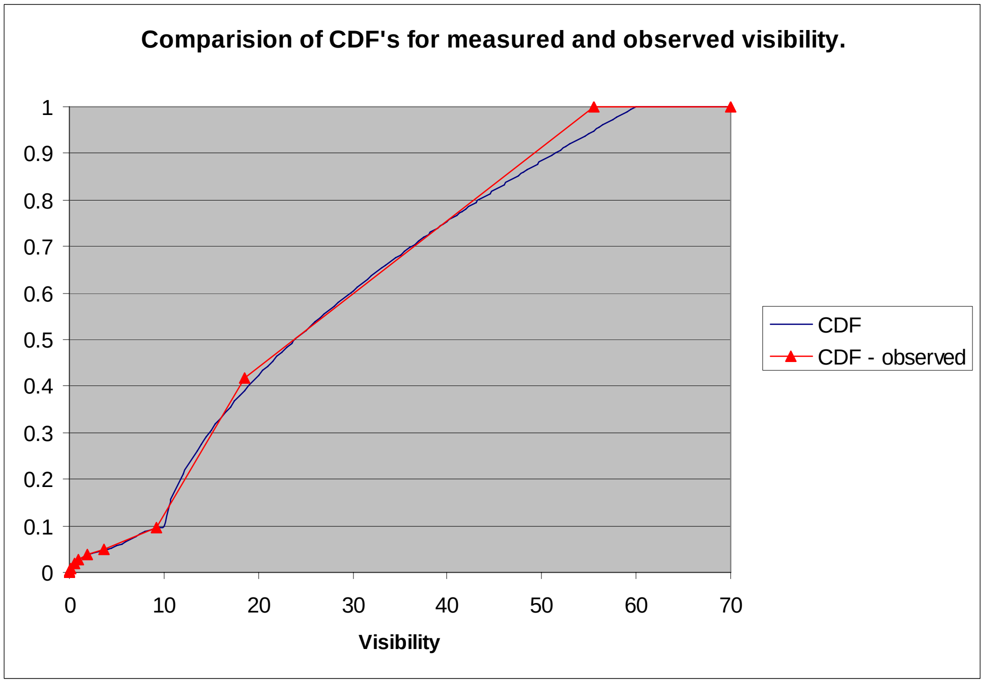

Storm
0.3
0.25
0.2
0.15
0.1
0.05
0
0
10
20
30
40
50
60

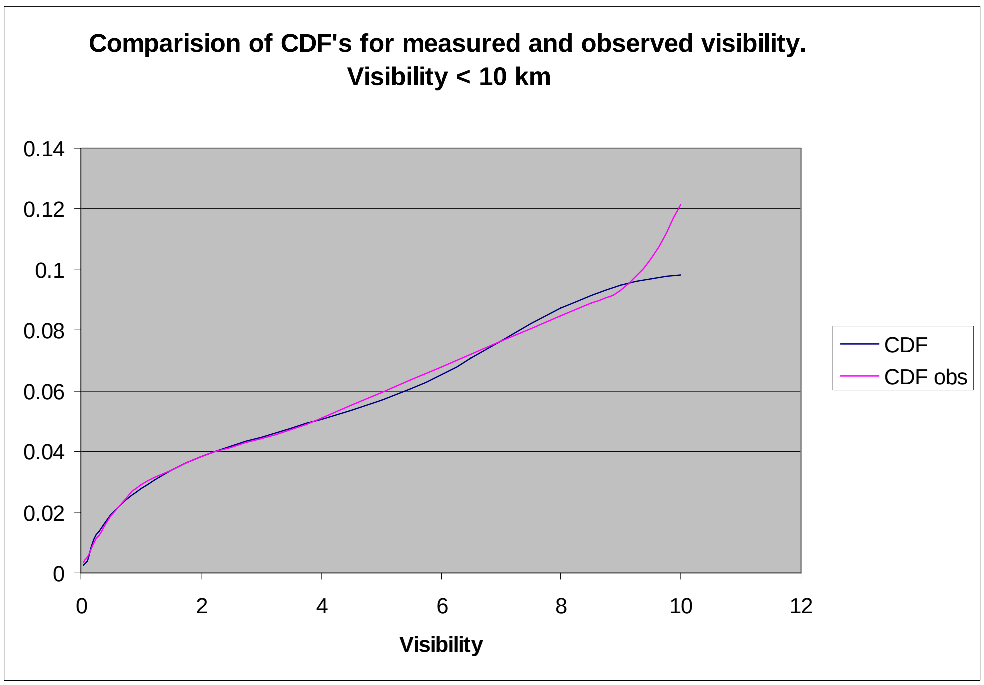

Rain and snow
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
0
10
20
30
40
50
60


Fog or heavy rain
3
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60

It is assumed that the conditional probability density functions for visibility to rain and snow are identical.

Comparison with measured data is shown below:





It is seen that the estimated marginal distribution resembles the observed data well.